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16. Abstract The Texas Department of Transportation (TxDOT) uses the Texas modified triaxial design procedure as a design check to the Flexible Pavement System (FPS) design method. This report describes a computer program researchers developed to check the adequacy of the thickness design from FPS based on the Mohr-Coulomb yield criterion. The modified triaxial (MTRX) program incorporates the following features: 1) characterization of pavement materials using layer moduli backcalculated from FWD deflections and strength properties determined from Texas triaxial tests or approximate procedures; 2) modeling of single and tandem axles to evaluate pavement damage potential under different axle configurations; 3) application of layered elastic theory to predict stresses under applied wheel loads (with the option of characterizing pavement materials as linear or nonlinear); and 4) application of Mohr-Coulomb failure criterion to check pavement damage potential. Instructions on the operation of the computer program are given in this report.					
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THE TEXAS MODIFIED TRIAXIAL (MTRX) DESIGN PROGRAM

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DISCLAIMER

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CHAPTER I

INTRODUCTION

The Texas Department of Transportation (TxDOT) uses the Texas modified triaxial design procedure as a design check to the Flexible Pavement System (FPS) program. The current version of this design program, FPS-19, uses the backcalculated layer moduli from falling weight deflectometer (FWD) measurements, and the expected number of 18-kip equivalent single axle loads (ESALs) to determine design thicknesses for the specified pavement materials. On many Farm-to-Market (FM) roads where the expected number of cumulative 18-kip ESALs is low, it is not uncommon to find trucks with wheel loads that exceed the standard 18-kip single axle load. These occasional overloads could give rise to subgrade shear failure, particularly under conditions where the base or subgrade is wet. Thus, pavement engineers check the results from FPS against the Texas modified triaxial design procedure to ensure that the design thickness provides adequate cover to protect the subgrade against occasional overstressing. In cases where the thickness requirement from the triaxial method is greater than the pavement thickness determined from FPS, current practice recommends using the pavement thickness based on the modified triaxial method unless the engineer can justify using the FPS results.

Since its original development more than 50 years ago, little modification has been made to the original triaxial design method. From experience, this method results in more conservative designs (relative to FPS) on low-volume roads, which make up the majority of the Texas highway mileage. While they recognize that the triaxial design method and FPS are based on different criteria, TxDOT engineers have raised the following issues concerning the present method:

1. applicability of using the Texas triaxial class (TTC) determined from tests on capillary saturated samples to the dry regions of the state (primarily west Texas);
2. characterization of stabilized layers using the cohesiometer;
3. rationality of using a safety factor of 1.3 to account for differences in pavement damage potential between single and tandem axle configurations; and

4. consideration of the lateral support provided by shoulders and the benefit this brings in minimizing edge failures.

To address the above issues, TxDOT originally developed a research project statement for Project 0-1775 that aimed to evaluate and identify improvements to the Texas triaxial design procedure. However, this project was not funded. Instead, a modification to an existing study, Project 0-1869, was made that added a task to evaluate the existing method under a supplemental funding of \$50,000. In view of the limited budget, the project monitoring committee along with researchers decided to concentrate on two of the four issues raised by TxDOT engineers, namely:

1. analysis of stabilized layers, and
2. use of a safety factor of 1.3.

The research effort led to the development of an alternative method for the triaxial design check that incorporates the following features:

1. characterization of pavement materials using layer moduli backcalculated from FWD deflections and strength properties determined from Texas triaxial tests or approximate procedures;
2. modeling of single and tandem axles (in lieu of using a safety factor of 1.3) to evaluate pavement damage potential under different axle configurations;
3. application of layered elastic theory to predict stresses under the applied wheel loads, with the option of characterizing pavement materials as linear or nonlinear (stress-dependent); and
4. application of Mohr-Coulomb failure criterion to check potential for pavement damage for the specified materials and wheel loads.

This report describes the computer program developed by the researchers to check the adequacy of the thickness design from FPS based on the Mohr-Coulomb yield criterion. The researchers note that this criterion also forms the basis for the existing Texas modified triaxial design procedure. The main differences between the existing method and the computer program developed in this project are in the characterization of the pavement materials and modeling of the wheel loads. For example, in lieu of specifying a cohesiometer value for a stabilized base, the alternative procedure uses the modulus and strength properties for the base material under consideration. This feature provides engineers

greater flexibility in analyzing different materials and permits them to use the same moduli specified in FPS-19 for the design check. Viewed from this perspective, there is a direct link between the alternative triaxial design method and FPS-19 that does not exist under the present method, where the required depth of cover is determined based on the Texas triaxial class of the subgrade. In addition, since pavement layers are characterized using fundamental material properties, TxDOT engineers can directly consider the effect of varying moisture conditions on the design check. Thus, a pavement design engineer in west Texas can test his or her materials under representative field moisture conditions and use the properties determined in the alternative procedure to perform the FPS design check.

While an alternative method has been developed, researchers recognize that more work is required before this procedure can be implemented statewide. In the opinion of the researchers, the work accomplished on Project 0-1869 has laid the groundwork by which future research and implementation efforts in this area can be directed. The computerized triaxial design method is presented in this report. It is organized into the following chapters:

1. [Chapter I](#) provides the motivation for the development work accomplished in this project, identifies its scope, and presents the features of the triaxial design program developed from this research.
2. [Chapter II](#) provides instructions on the operation of the Texas Modified **TRiaXial** program (**MTRX**).
3. [Chapter III](#) provides recommendations for implementing the computer program.
4. The [appendix](#) documents the methods available in MTRX to establish the strength properties for evaluating the FPS thickness design.

Conducting a triaxial design check using MTRX will require the following information from the user:

1. modulus, Poisson's ratio, and thickness of each pavement layer;
2. average of the ten heaviest wheel loads; and
3. Texas triaxial class of the subgrade.

The above data may be obtained from the flexible pavement design, and represent the minimum that are required to run MTRX. Note that running the program and getting good results are two different things. To do an adequate analysis, the engineer should know the properties of the materials to be placed and model the pavement realistically. Good

engineering practice will require an effort to search published information, review past experience, and/or run tests to characterize the materials for a given problem.

CHAPTER II

OPERATION OF THE MTRX DESIGN CHECK PROGRAM

This chapter provides a user's guide to MTRX version 1.0 that the researchers developed for evaluating the structural adequacy of pavement designs based on the Mohr-Coulomb yield criterion. MTRX is used to check the potential for pavement damage resulting from one application of a very heavy wheel load with magnitude given by the average of the ten heaviest wheel loads (ATHWLD) used in pavement design. The program requires a microcomputer operating under the Windows 9x, 2000 or NT environment. To install MTRX, run the setup file *MTRXSETUP.EXE* provided with the program disk and follow the on-screen instructions. After installation, double click on the MTRX program icon on your desktop to run MTRX. The program brings up the opening screen shown in [Figure 1](#). Click anywhere on this screen to proceed to the main menu shown in [Figure 2](#). From this menu, you may specify the parameters characterizing the pavement and load for a given run. Before going further, here are two simple guidelines for navigating through the different menus of MTRX:

1. To select a particular option on the screen, move the pointer to it and then click with the left mouse button.
2. To enter data for a particular variable, move the cursor to the field or cell. Then type in the required data. To position the cursor to an input field, move the pointer to the field and click on it.

By clicking on the options in the main menu, the user can access any of the available functions for opening an existing input file, specifying material parameters (i.e., resilient and strength properties), saving input data, running a triaxial design check, and viewing, printing and saving program output. The succeeding sections describe these functions.

MAIN MENU

[Figure 2](#) illustrates the main menu that is displayed after loading the MTRX program. First, you should specify the number of layers above the rigid bottom, which is restricted to



Figure 1. MTRX Opening Screen.

three or four. By default, the program initially assumes three pavement layers, as indicated in [Figure 2](#). To specify four layers, simply click on **4 Layers** to select it. When you do, another row will be added in the menu for specifying the properties of the fourth pavement layer. While the minimum number of pavement layers is three, you may evaluate a full-depth asphalt pavement, consisting of two layers (asphalt concrete over subgrade), by specifying three layers and entering the same properties for the first and second layers.

For each layer, you will have to enter its modulus, Poisson's ratio, and thickness. MTRX uses English units so you need to enter the modulus in lbs/in² (psi) and the thickness in inches. The values that you enter should correspond to the properties that were used to determine the pavement design for a given project using FPS. In addition, MTRX requires the cohesion (in psi) and friction angle (in degrees) that define the Mohr-Coulomb failure envelope for the subgrade. The program uses these properties to determine whether the existing depth of subgrade cover is adequate or not. You may determine these properties

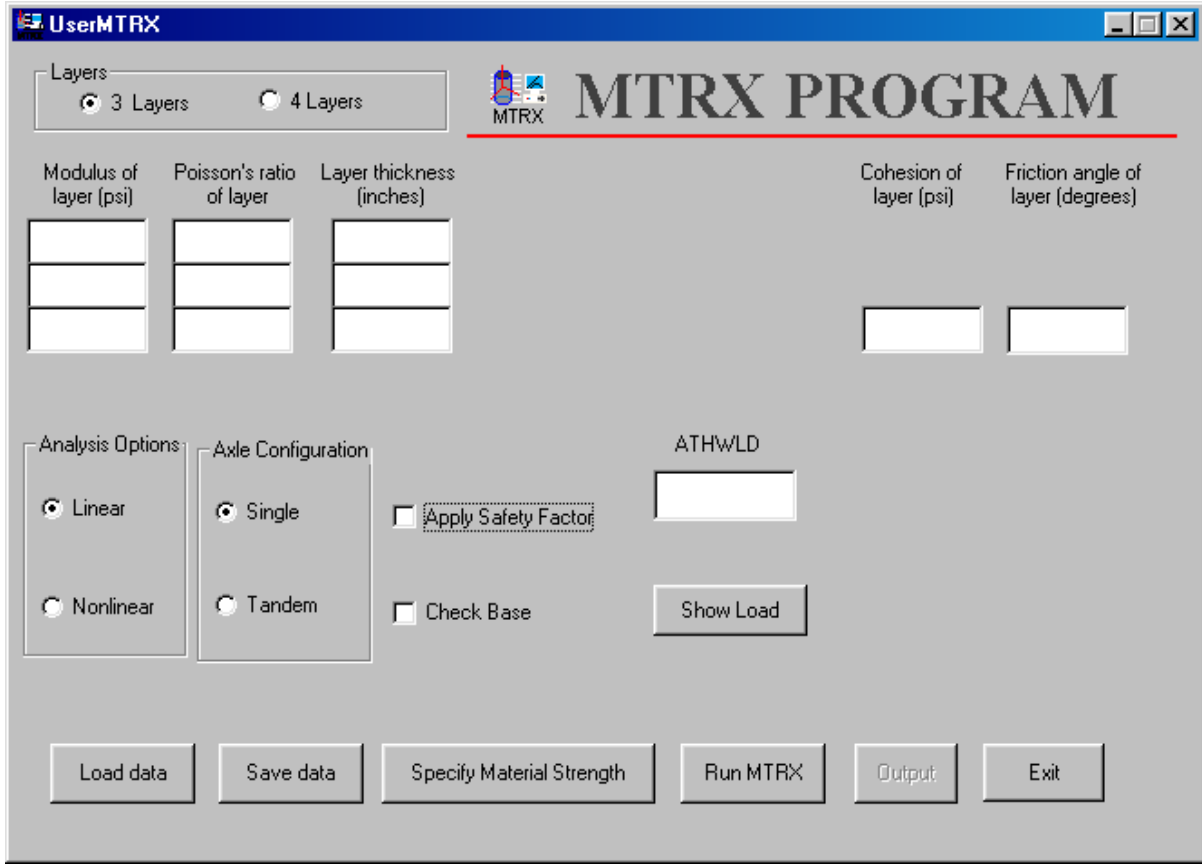


Figure 2. Main Menu of MTRX Program.

by running triaxial tests on molded samples of the subgrade material found in a given project. If triaxial test data are available, you may use MTRX to determine the cohesion and friction angle given the compressive strengths determined at two or more confining pressures. Researchers recommend that you run triaxial tests whenever possible. However, in the absence of such data, MTRX has other options for estimating the failure envelope that are described in “Options for Specifying Strength Properties” later in this chapter.

The program uses layered elastic theory to predict the stresses induced under load for the given pavement. These stresses are then checked against the Mohr-Coulomb failure envelope to evaluate the potential for pavement damage resulting from one application of a very heavy wheel load characterized by the ATHwLD used in pavement design. By default, the program runs a linear analysis to predict the stresses. However, for the advanced user, a nonlinear option is included to permit modeling of the stress-dependency. The nonlinear

analysis option is described in “Nonlinear Analysis Option” later in this chapter. To select an analysis option, simply click on **Linear** or **Nonlinear** in the main menu (Figure 2).

MTRX also permits modeling of single and tandem axle loads. Researchers incorporated this capability to provide an alternative to the present practice of applying a safety factor of 1.3 to the ATHWLD when the percent tandem axles is greater than 50. With MTRX, you may model a tandem axle load directly by clicking on **Tandem** in the main menu. In this case, it is not necessary to apply the safety factor although you may still do so by clicking **Apply Safety Factor** in the main menu. When you do, a check appears inside the option box indicating that the program will apply the safety factor to the calculations. To deselect this option, simply click on its box again.

You may load an existing data file by clicking on **Load data** in the main menu. This brings up the dialog box shown in Figure 3 where you can select the particular file to load into the program. Simply highlight the file name in the dialog box. Then click on **Open** to read the data into MTRX. The main menu displays the data as shown in Figure 4. To help users learn the program, two sample input files named *Example Data1.DAT* and *Example Data2.DAT* are copied into the MTRX program directory during installation. You may try loading *Example Data1.DAT* as an exercise on using the **Load data** function. The data in this file are displayed in Figure 4 where a three-layer pavement is characterized with the moduli, Poisson’s ratios, and thicknesses shown. The subgrade has a cohesion of 4 psi and a friction angle of 40.1°. Also note that a single axle load is specified. The load per wheel of the single axle is determined from the ATHWLD that is given as 12,000 lbs in Figure 4. To show the load characteristics, click on **Show Load** in the main menu. The program then displays the wheel load, tire pressure and tire spacing on the right side of the main menu as illustrated in Figure 5. Since the ATHWLD is transmitted to the pavement on dual tires, the wheel load is taken as half of the ATHWLD. However, the wheel load is multiplied by the safety factor of 1.3 if the user checks this option in the main menu. Thus in Figure 5, the wheel load is displayed as 7800 lbs ($\frac{1}{2} \times 12,000 \times 1.3$). This wheel load is assumed for all tires of the axle.

To close the window displaying the load characteristics, click on **Hide Load** in the main menu shown in Figure 5. Note that if you do not specify the tire inflation pressure and tire spacing, MTRX will use the default values of 100 psi and 14 inches for these variables,

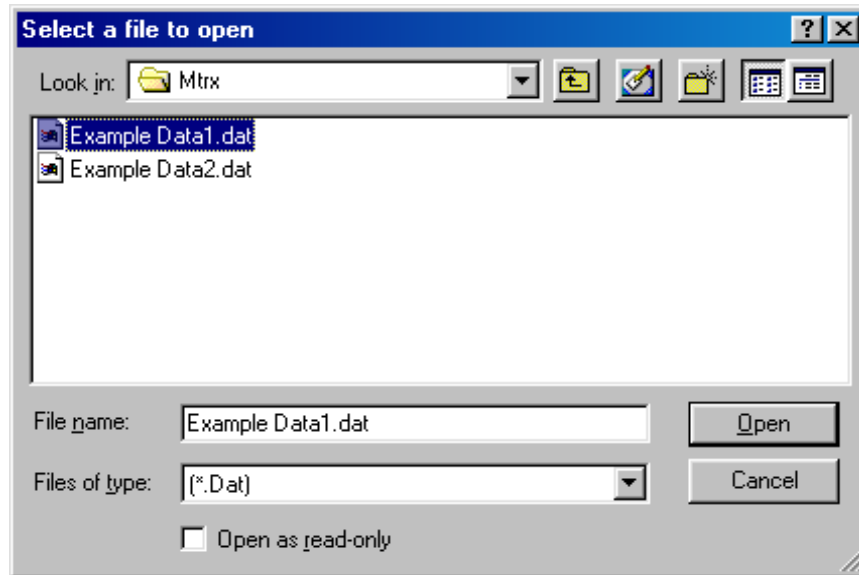


Figure 3. Dialog Box to Load an Input Data File into MTRX.

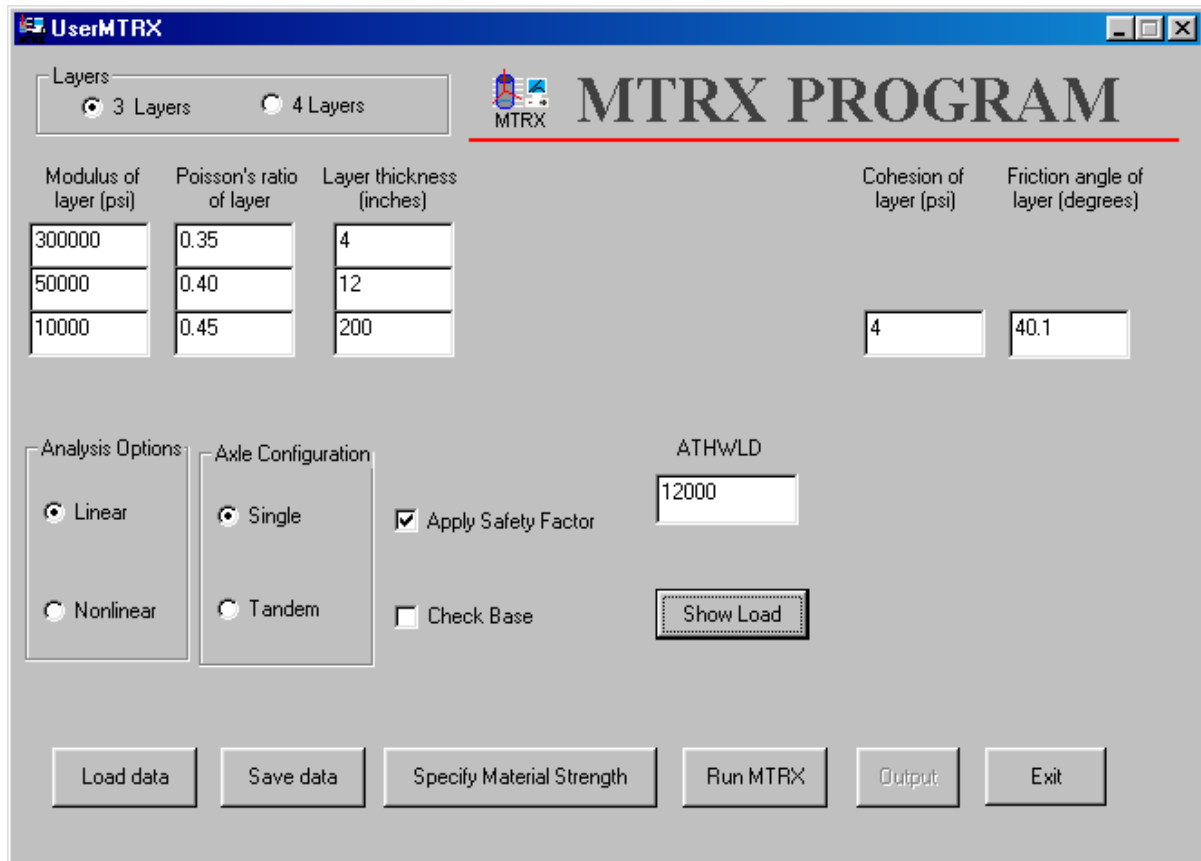


Figure 4. Main Menu Displaying Data Read from an Existing Input File.

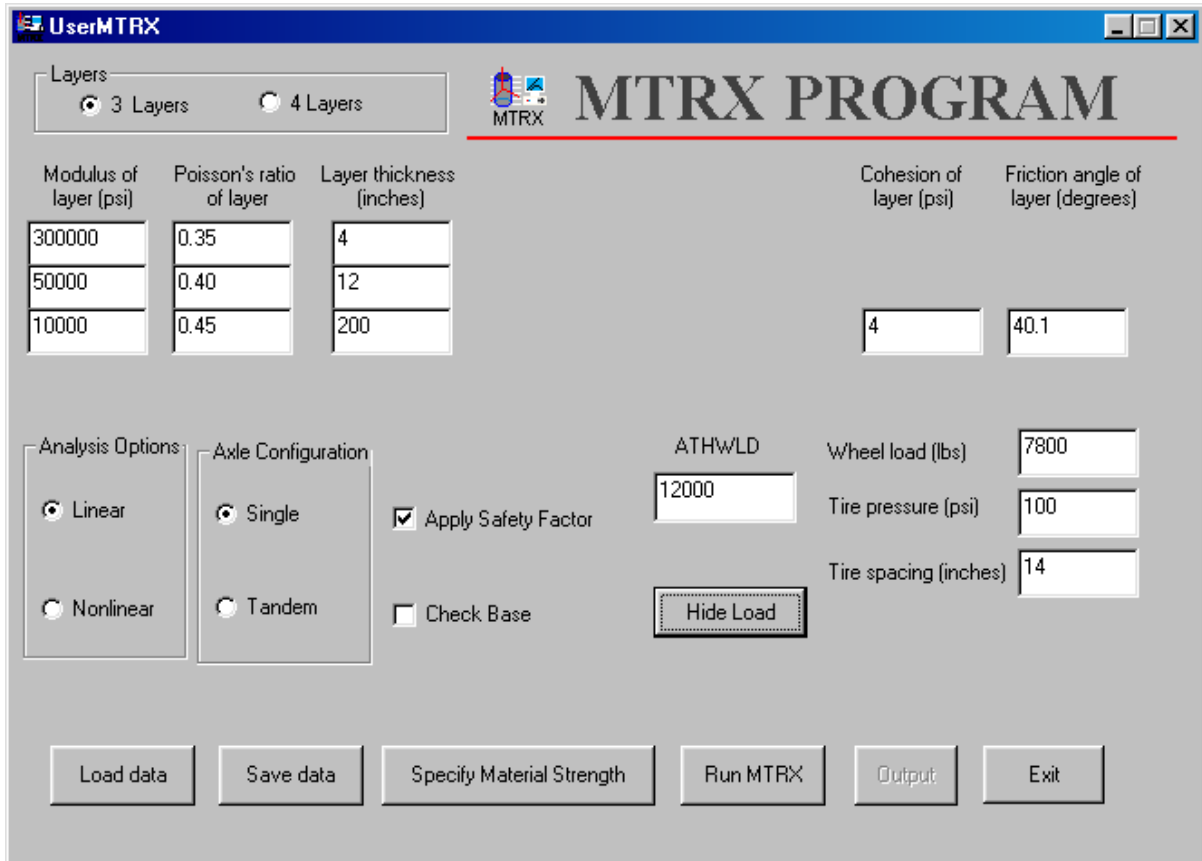


Figure 5. Display of the Load Characteristics for a Single Axle Configuration.

respectively. Thus, you only need to specify the ATHWLD, axle configuration, and whether the safety factor is to be applied or not. For tandems, the spacing between axles defaults to 54 inches. If you want to use another spacing, click on **Show Load** to view the load characteristics (Figure 6) and change the axle spacing accordingly. Additionally, you may change the tire inflation pressure and tire spacing.

The **Check Base** option is provided to evaluate whether overstressing is predicted in the base for the given load and pavement design. Since the existing modified triaxial design procedure does not check the base, MTRX conducts this evaluation only if you specifically selected the option in the main menu. If you wish to evaluate the base, you will have to specify the cohesion and friction angle for the material. For these properties, default values of 10 psi and 30° are used, respectively, in the absence of any user input. The authors recommend running triaxial tests to determine the strength properties of the base. However,

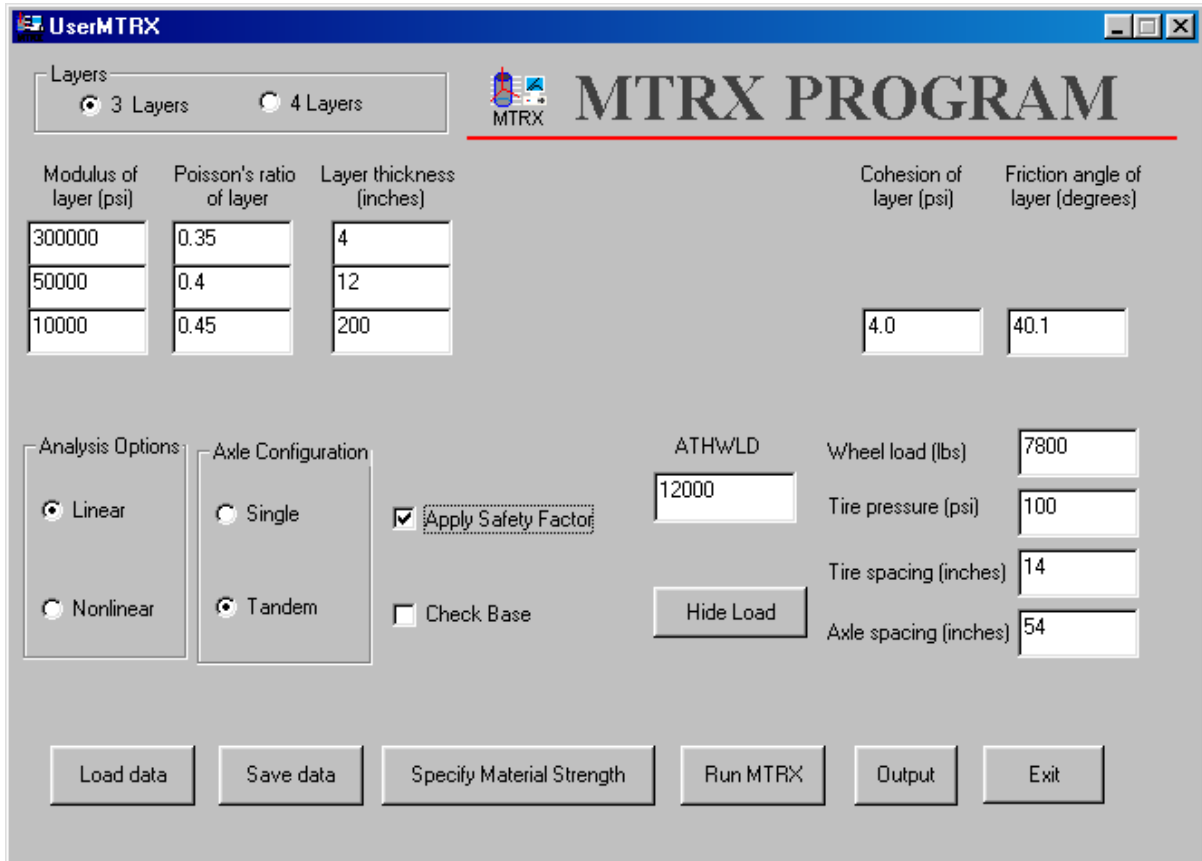


Figure 6. Display of the Load Characteristics for a Tandem Axle Configuration.

should it not be possible to run these tests, there are a number of methods built into MTRX to estimate the cohesion and friction angle that are described in “Options for Specifying Strength Properties” in this chapter. By default, MTRX does not perform a check of the base.

After specifying the data for a given evaluation, you may save your input by clicking on *Save data* in the main menu. The dialog box shown in [Figure 7](#) is then displayed where you can specify the name of the file to write the data to. You may then run the program using the specified data by clicking on *Run MTRX* in the main menu. This function is described in the next section.

RUNNING AN EVALUATION AND VIEWING OUTPUT

The run time screen shown in [Figure 8](#) is displayed during the evaluation of a given pavement design. If this evaluation shows that no overstressing is predicted in the subgrade, MTRX displays the message box shown in [Figure 9](#) to let you know that the given pavement

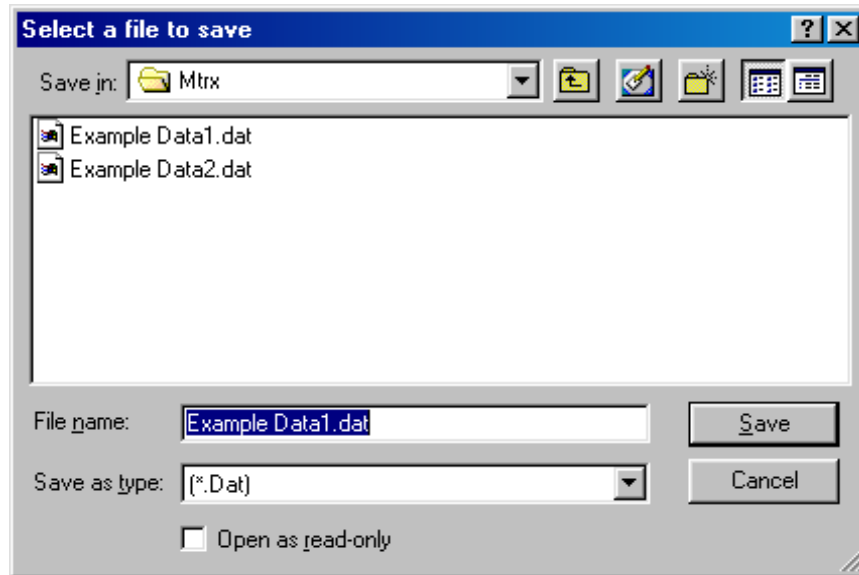


Figure 7. Saving the Input Data in MTRX.

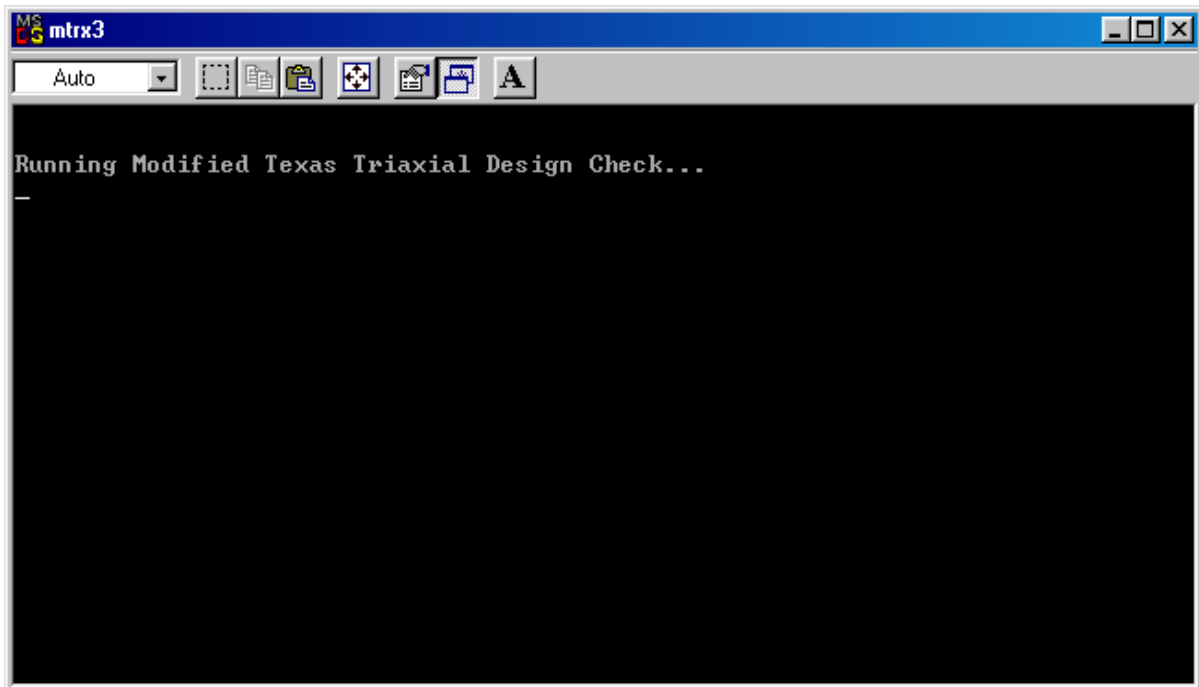


Figure 8. Run Time Screen Displayed During an Analysis.

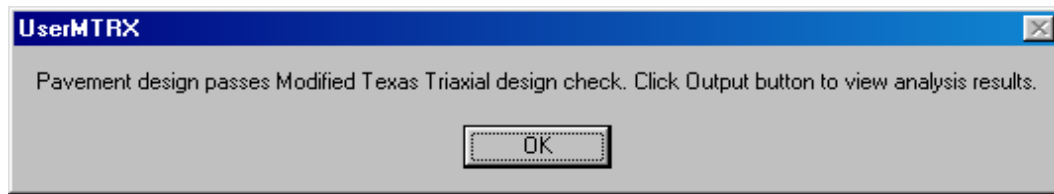


Figure 9. Message Displayed when Pavement Design Passes Triaxial Design Check.

passes the Texas triaxial design check. If the pavement design is inadequate, the program will automatically search for the minimum base thickness required to prevent overstressing at the top of the subgrade for the given load. During this time, the run time screen will display each trial base thickness and the corresponding value of the Mohr-Coulomb yield function (Figure 10). An adequate base thickness is indicated when the value of the yield function becomes negative. At the end of the analysis, MTRX will display a message box that shows the current design base thickness and the minimum value required to prevent overstressing the subgrade (corresponding to a predicted yield function just below zero). Figure 11 illustrates the message box that is displayed when the design base thickness is insufficient to prevent overstressing the subgrade.

The information that is displayed in the message box at the end of an analysis is typically the only output necessary for most design applications. However, the program has an output function that provides additional details of the analysis. The following description of the output function is not necessary to learn how to use the program so you may skip this part of the user's guide and move on to "Options for Specifying Strength Properties," which covers the methods available in MTRX to specify the strength properties of a given material. The remainder of this section describes other information that is output by MTRX.

Clicking on *Output* in the main menu brings up the screen given in Figure 12. As shown, the Mohr-Coulomb yield criterion is checked at a number of positions along the top of the subgrade corresponding to locations below the outside tire edge, middle of the tire, inside tire edge and midway between tires. At these locations, the induced stresses under load are predicted and used with the following equation to calculate the values of the yield function (Chen and Baladi, 1985):

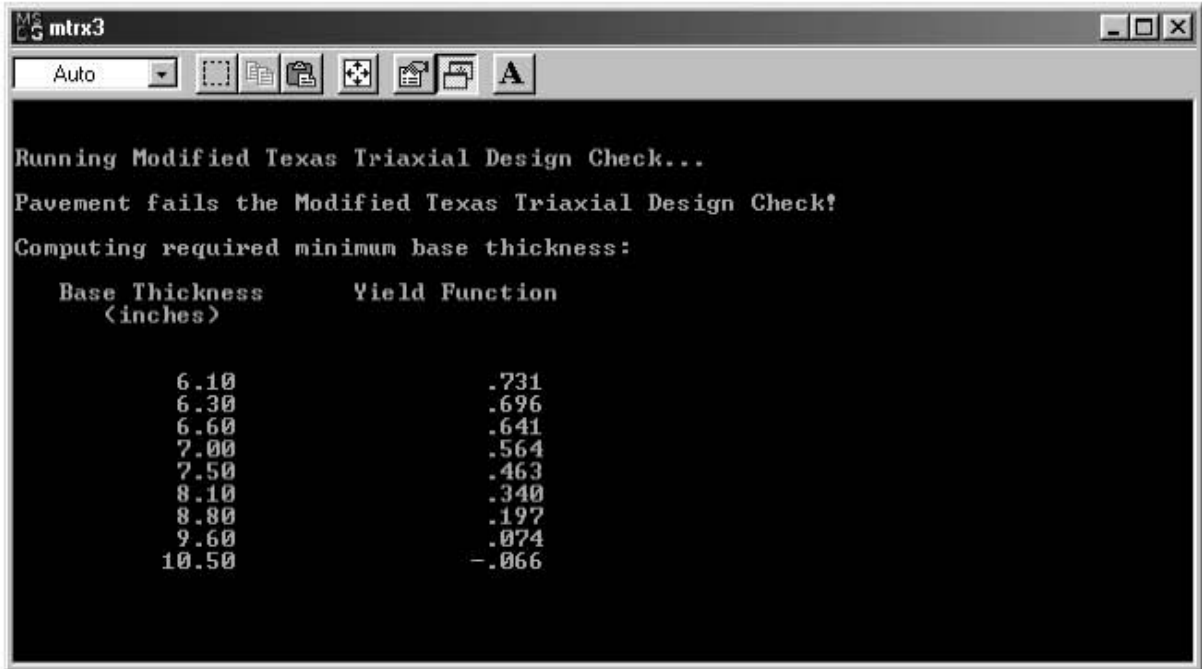


Figure 10. Run Time Screen During Search for Minimum Required Base Thickness.



Figure 11. Message Displayed when Pavement Design Fails Triaxial Design Check.

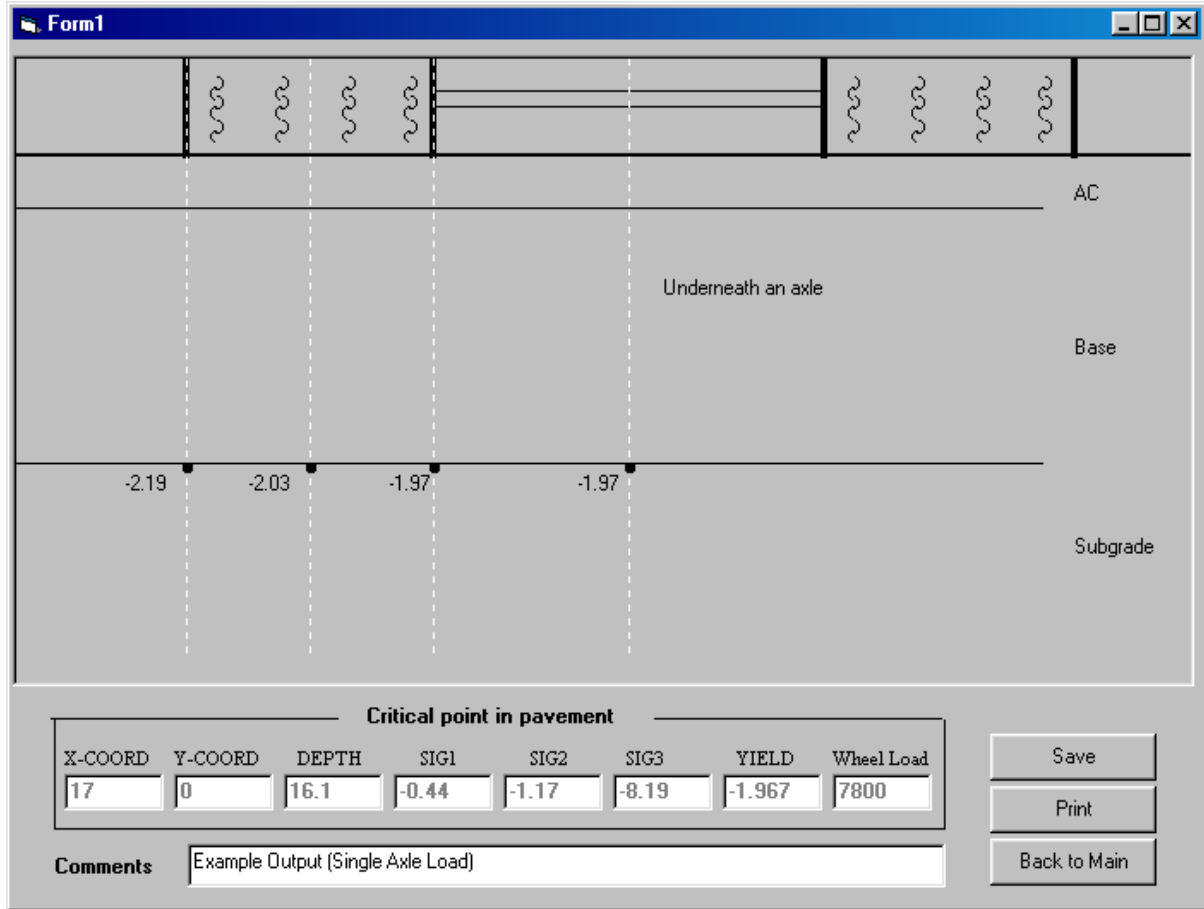


Figure 12. Output Screen of Computed Mohr-Coulomb Yield Function Values.

$$f = \frac{I_1}{3} \sin(\phi) + \sqrt{J_2} \sin\left(\theta + \frac{\pi}{3}\right) + \frac{\sqrt{J_2}}{\sqrt{3}} \cos\left(\theta + \frac{\pi}{3}\right) \sin(\phi) - c \cos(\phi) \quad (1)$$

where,

- I_1 = first stress invariant,
- J_2 = second deviatoric stress invariant,
- c = cohesion,
- ϕ = friction angle, and
- θ = Lode angle.

Physically, the first stress invariant is associated with volume change in a material under loading, while the second deviatoric stress invariant is associated with distortion of the material. The Lode angle is calculated from the equation:

$$\theta = \frac{1}{3} \cos^{-1} \left(\frac{3\sqrt{3}}{2} \frac{J_3}{J_2^{3/2}} \right) \quad (2)$$

where J_3 is the third deviatoric stress invariant. From mechanics, I_1 , J_2 and J_3 , are computed from the principal stresses, σ_1 , σ_2 , and σ_3 that are predicted at a given point within the pavement from layered elastic theory. The equations for determining the stress invariants are:

$$I_1 = \sigma_1 + \sigma_2 + \sigma_3 \quad (3)$$

$$J_2 = \frac{1}{6} \left[(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2 \right] \quad (4)$$

$$J_3 = \left(\sigma_1 - \frac{I_1}{3} \right) \left(\sigma_2 - \frac{I_1}{3} \right) \left(\sigma_3 - \frac{I_1}{3} \right) \quad (5)$$

The onset of yield or inelastic deformation is predicted when the value of the yield function is zero, i.e., $f = 0$ in Eq. (1). When this condition is plotted for the Mohr-Coulomb yield function, the surface illustrated in [Figure 13](#) is obtained. Stress states falling inside the yield surface correspond to elastic behavior, i.e., below yield. Mathematically, this is equivalent to a computed yield function value less than zero, i.e., $f < 0$, for the given pavement and load. It is observed from [Figure 13](#) that the cross-sectional area of the Mohr-Coulomb yield surface increases as the hydrostatic stress component, represented by the mean stress, $I_1/3$, in Eq. (1) increases. Physically, this means that a material subjected to higher confinement will sustain a higher level of stress before reaching the yield condition. The computed yield function values are used in MTRX to determine whether the given pavement passes the triaxial design check or not. When the computed yield functions values from the analysis are all negative, such as illustrated in [Figure 12](#), pavement damage from one application of the ATHWLD is deemed unlikely. However, when one or more points are predicted to be at yield, pavement damage may occur so a thicker base is indicated.

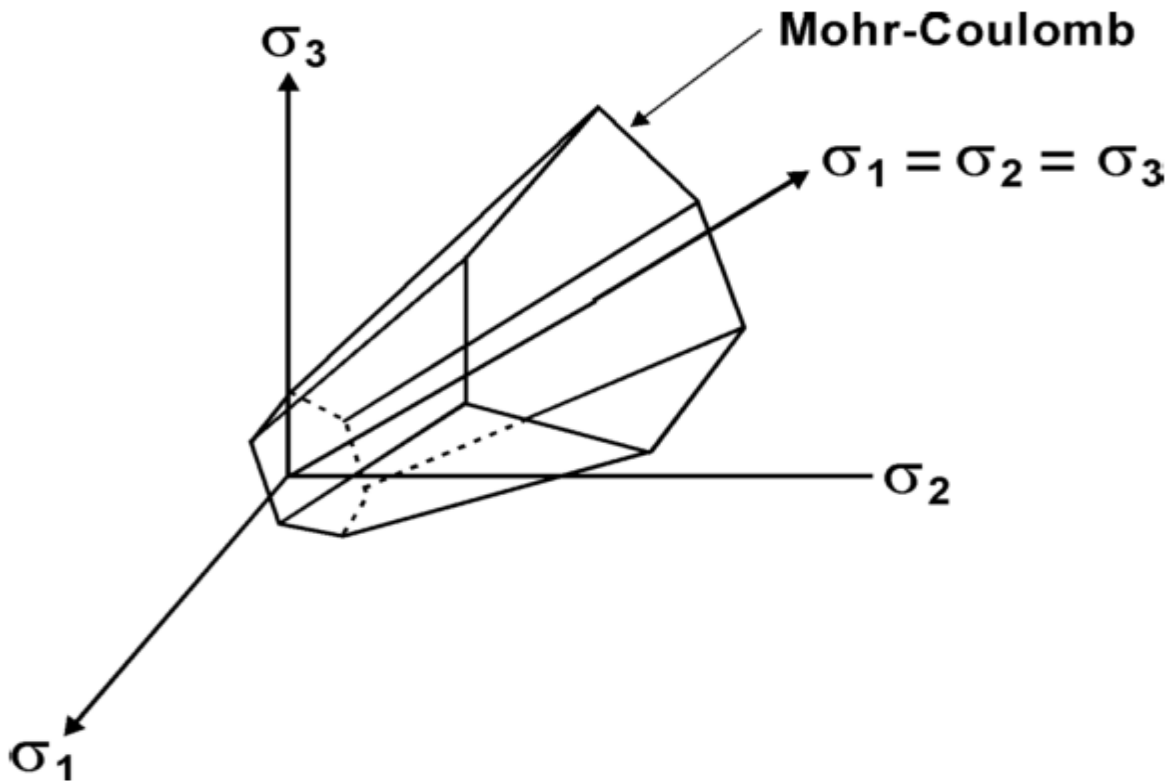


Figure 13. Graphical Illustration of Mohr-Coulomb Yield Criterion.

In the case where overstressing in the base is evaluated, the base is subdivided into three layers and the Mohr-Coulomb yield functions are then evaluated at three different depths corresponding to the middle of the top sublayer, middle of the base, and near the bottom of the base. As with the evaluation of the subgrade, the yield functions are also computed at different lateral positions within the base corresponding to the outside tire edge, middle of the tire, inside tire edge, and midway between dual tires. In the case of tandem axles, the stresses at the same positions are evaluated midway between the axles. Values of the Mohr-Coulomb yield function at this location are displayed in another screen similar to [Figure 12](#).

The location of the critical point with the greatest value of the yield function is shown at the bottom of the output screen along with the principal stresses and yield function value computed at that point. You may print the chart illustrated in [Figure 12](#) by clicking on *Print* in the output screen. There is a field available to type in comments related to the analysis you just made. You may, for example, type in identifiers for the project just analyzed.

Comments that you type are also printed with the output to provide you a way of labeling the printed results. [Figure 14](#) shows an example printout of the results from an analysis. The printout shows the information displayed in the output screen ([Figure 12](#)); identifies the name of the file where the results have been saved; gives the date and time of the analysis; and specifies whether the pavement passes the modified triaxial design check or not. If the pavement fails the design check, the printout will also show the minimum required base thickness to prevent overstressing the subgrade for the given ATHWLD. Note that the file name is only printed if you saved the results prior to printing. If you did not, the file name is blank in the printout. To save the results, click on *Save* in the output screen ([Figure 12](#)). The dialog box illustrated in [Figure 15](#) is then displayed for you to specify the name of the file to write the results to. After viewing, saving, and/or printing the results, you may go back to the MTRX main menu by clicking on *Back to Main* in the output screen.

OPTIONS FOR SPECIFYING STRENGTH PROPERTIES

If you click on *Specify Material Strength* in the MTRX main menu ([Figure 4](#)) or double click on either the cohesion or friction angle field, the options available for specifying the strength properties are displayed. As shown in [Figure 16](#), the available options are:

1. determining the strength properties (cohesion and friction angle) using test data from triaxial tests conducted on material specimens;
2. estimating strength properties based on the strength determined from unconfined compressive tests; and
3. using the known Texas triaxial class to estimate the strength properties for a given material.

As stated previously, the recommended approach is to run triaxial tests on the material to be analyzed. The standard test method, Tex-117-E, may be used to determine the strength properties. It is recognized that not all districts are equipped or staffed to run triaxial tests on a regular basis. For this reason, the researchers have included approximate methods in MTRX to estimate the strength properties. The [appendix](#) documents these methods. In the following subsections, researchers present the options included in the program for specifying the cohesion and friction angle of a given material.

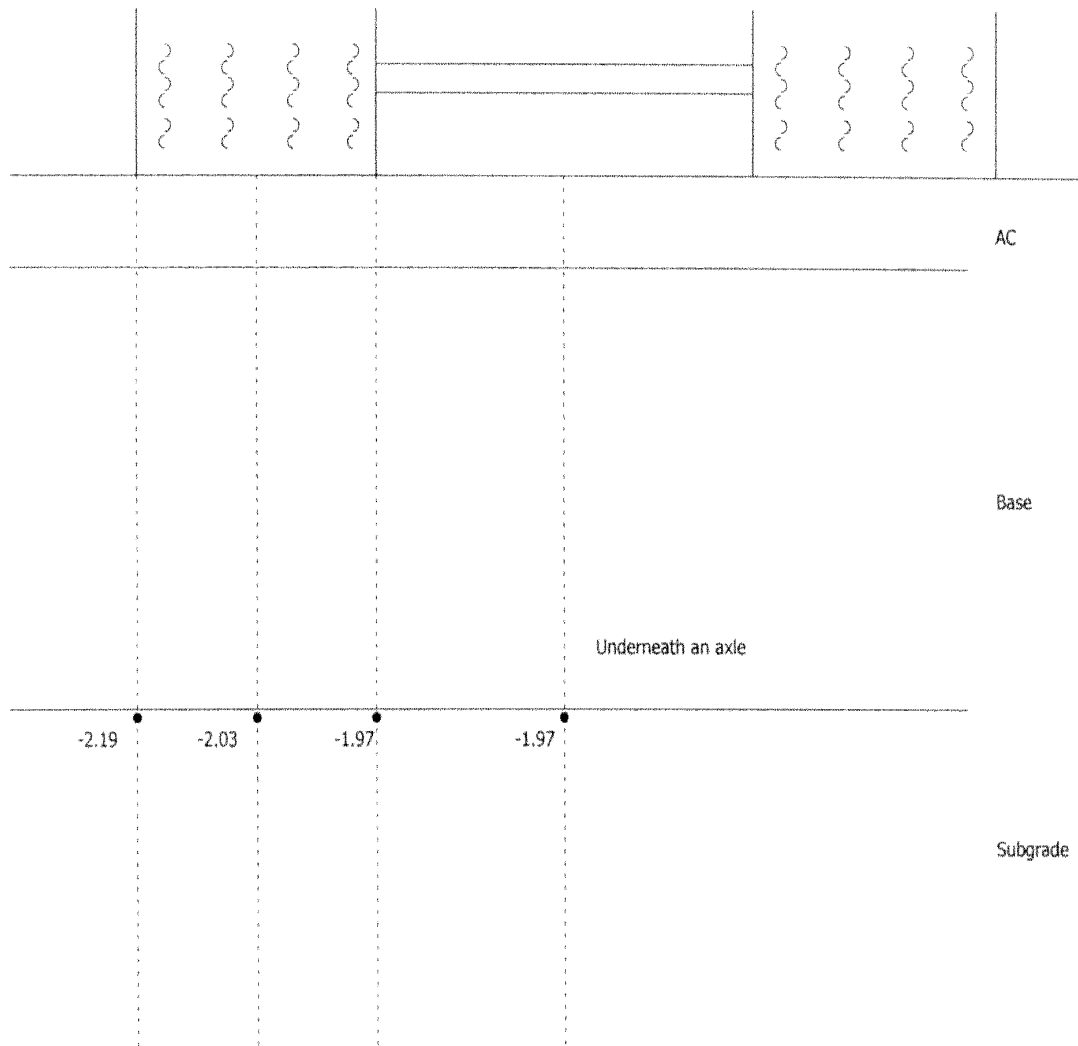
Structural Adequacy Analysis Results

Comment : Example Output (Single Axle Load)

File Name : C:\MTRX\Example Output1.txt

Date : 5/9/01 Time : 1:11:31 PM

Pavement design passes Modified Texas Triaxial design check.



Critical point in pavement

X coordinate	Y coordinate	Z coordinate	Sig1	Sig2	Sig3	Yield	Wheel load
17	0	16.1	-0.44	-1.17	-8.19	-1.967	7800

Figure 14. Example Printout of Analysis Results from MTRX.

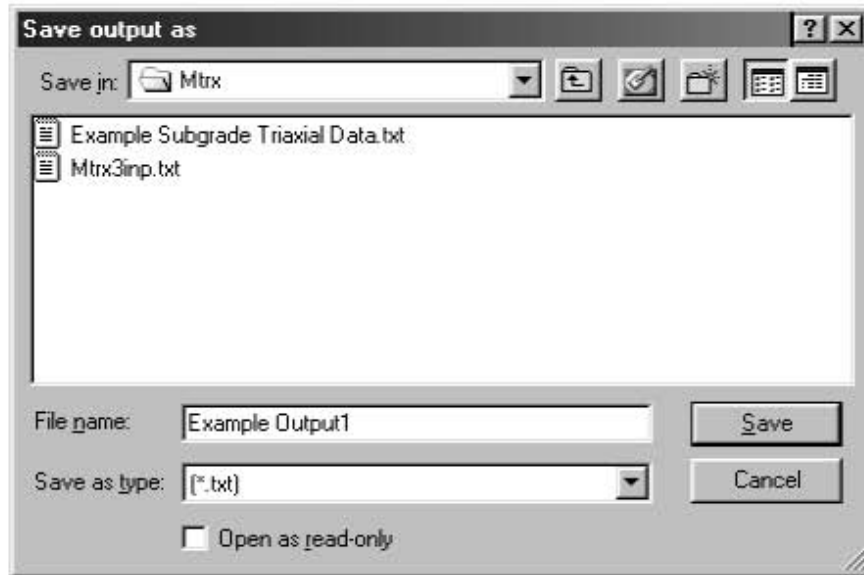


Figure 15. Dialog Box to Save Results from MTRX.

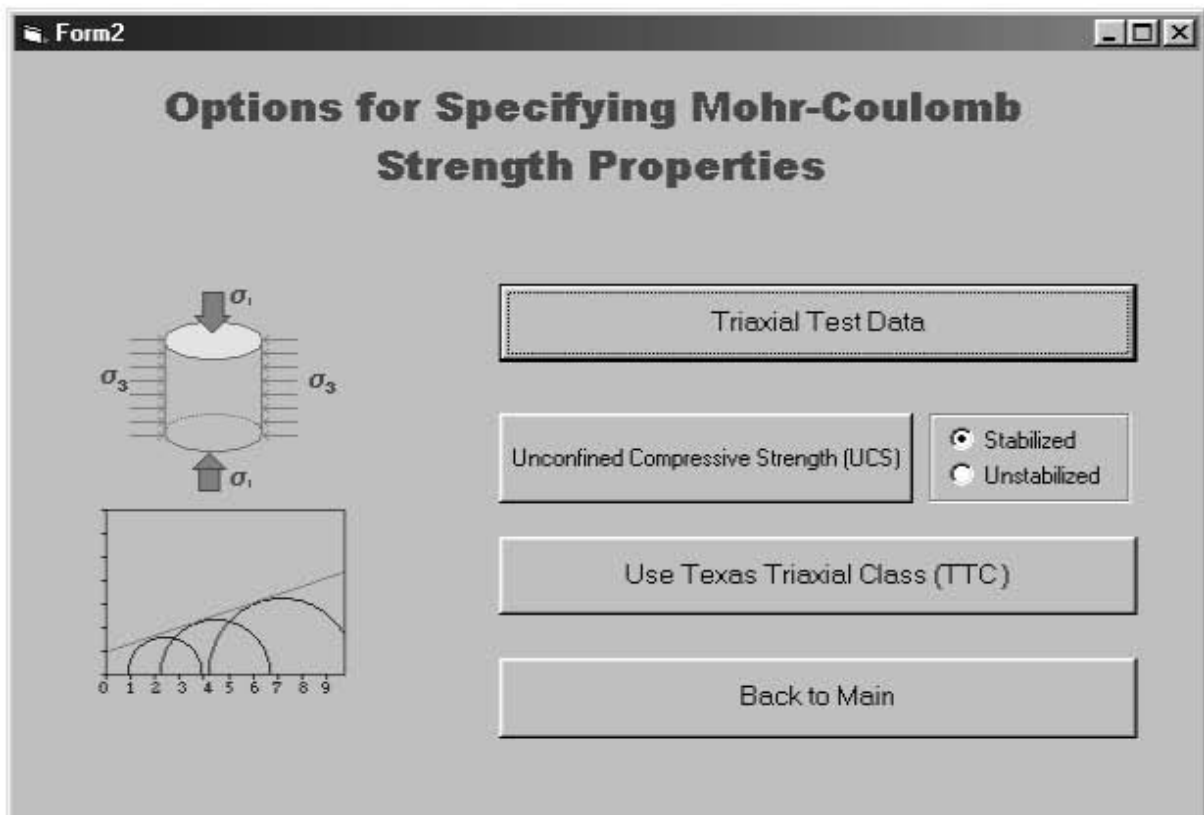


Figure 16. Options for Specifying Strength Properties in MTRX.

Determining Strength Properties from Available Triaxial Test Data

If you conducted triaxial tests, click on *Triaxial Test Data* in the menu given in [Figure 16](#) to use the program in determining the cohesion and friction angle. To use this option, you will need to have the compressive strengths determined at two or more confining pressures. After you click on *Triaxial Test Data*, MTRX displays the form shown in [Figure 17](#). Specify the layer number of the material on which you conducted triaxial tests. For the subgrade, this would be “3” or “4” depending on whether you are analyzing a three- or four-layer pavement. Note that the layer number should correspond to the subgrade or to the base (if you use the *Check Base* option). If you specify an invalid layer number, the program will notify you. The program automatically sets the layer to the number for the subgrade when the *Check Base* option is not selected in the main menu.

There are seven buttons at the bottom of the form shown in [Figure 17](#). The *Input data* button allows you to enter corresponding values of confining pressure and failure stress. To do this, type a value of lateral pressure in the *Confining pressure* field and the corresponding value of the failure stress in the *Load at failure* field. Then, click on *Input data* to accept your entries. The corresponding data pair is then displayed under the *Confining pressure* and *Failure stress* columns of the form. Repeat this sequence for other pairs of triaxial test data until you have entered all data.

You may save your input by clicking on *Save data* in the form shown in [Figure 17](#). Likewise, you may load an existing triaxial data file by clicking on *Load data*. The file *Example Subgrade Triaxial Data.TXT* that is copied to the MTRX program subdirectory during installation is a sample triaxial data file that you may use in learning the operation of this function for determining strength properties. This file contains data from Texas triaxial tests conducted on sandy clay subgrade specimens molded from material taken along FM 782 in Rusk County to evaluate a superheavy load move. The sample data shown in [Figure 17](#) were read from this file.

The *Clear a row* or *Clear all* buttons allow you to edit the data displayed in the menu. To clear a pair of confining pressure and failure stress previously entered, highlight the record by clicking on either one of these items. Then click on *Clear a row* to delete the highlighted data pair. To delete all data, click on the *Clear all* button.

C - ϕ Triaxial Test Program

Name of test	Confining pressure (psi)	Failure stress (psi)
<input type="text"/>	0	14.8
	3	34.2
	5	41.8
	10	63.8
	15	86.7

Confining pressure (psi)

Load at failure (psi)

Texas Transportation Institute
 Texas A.M University
 College Station, TX 77843-3135

Figure 17. Form to Enter Compressive Strengths at Different Confining Pressures.

Once you have entered all triaxial test data, you may click on ***C & Angle*** to determine the cohesion and friction angle of the material. The results of the calculations are presented in the output screen illustrated in [Figure 18](#) where the Mohr's circles and the failure envelope are plotted. Click on ***Print*** to get a hardcopy of the chart shown. When you are finished viewing the results, click on ***Back*** to return to the form shown in [Figure 17](#). From here, you may evaluate the strength properties of another material or return to the main menu by clicking on the ***Back*** button of the form. The main menu displays the cohesion and friction angle determined from the analysis of triaxial test data.

Estimating Strength Properties from Unconfined Compressive Strength (UCS)

As indicated in [Figure 16](#), options for estimating the strength properties based on UCS are grouped according to whether the material is stabilized or unstabilized. It is

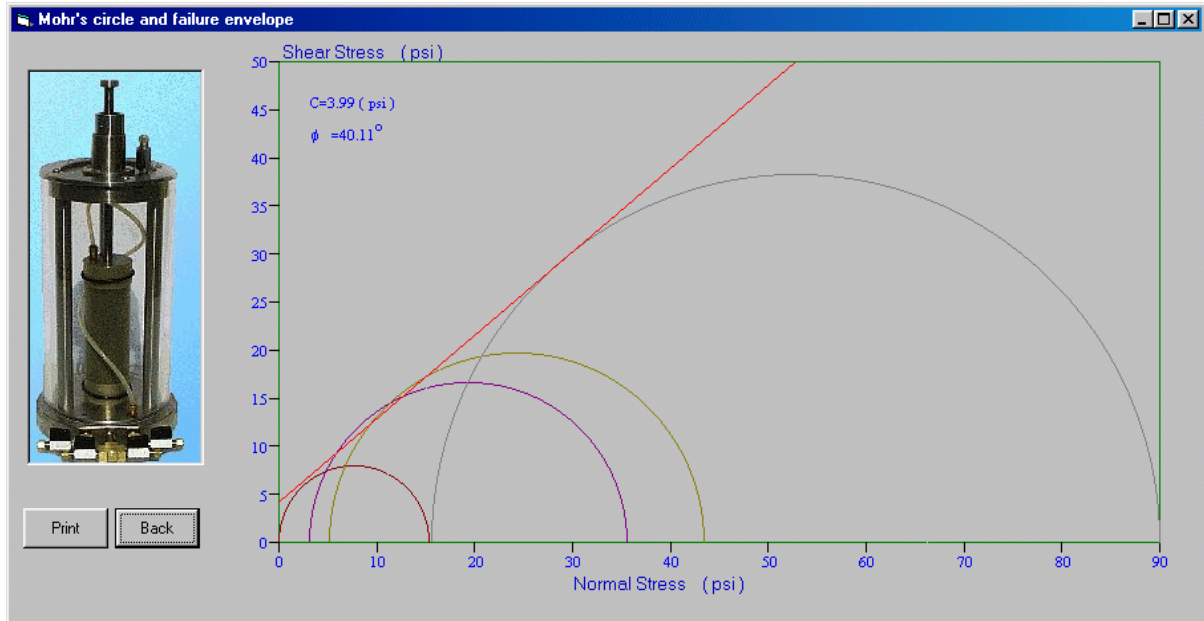


Figure 18. Determining Failure Envelope from Triaxial Test Data.

emphasized that these methods are approximate and were developed based on information obtained from the literature. You may use the methods for stabilized materials to evaluate pavement designs that incorporate asphalt-, lime-, or cement-treated base materials when the **Check Base** option is selected in the main menu. Note that these methods are only used to estimate the strength properties of stabilized materials for the case where you want to evaluate the potential of overstressing the base for the given pavement and load. Otherwise, the strength properties of the base layer are not necessary to run the program.

Click on **Unconfined Compressive Strength (UCS)** in the screen shown in Figure 16 to use the options for stabilized materials (note that you must first select the **Stabilized** option in the screen shown in Figure 16). The dialog box shown in Figure 19 is then displayed for you to specify the type of stabilized material to be evaluated. If the material is asphalt-stabilized, click on **Asphalt Stabilized** in the dialog box and specify the layer number and the UCS for the material. Note that you only need to specify the layer number if you selected the **Check Base** option in the main menu. If you did not select **Check Base**, the program automatically sets the number to that of the subgrade layer.

When you have entered the UCS, click on **Accept** to confirm your entries and estimate the cohesion. For asphalt-stabilized base layers, the friction angle is assumed to be zero in determining the cohesion from the UCS. This approximation is used since the lower

The image shows a software window titled "Form2" with the main heading "UCS Option—Stabilized Materials". On the left side, there are three radio button options: "Asphalt Stabilized" (which is selected), "Lime-stabilized", and "Cement-treated". To the right of these options, there are two input fields. The first is labeled "Layer" and contains the number "2". The second is labeled "UCS" and contains the number "200". At the bottom right of the dialog, there are two buttons: "Accept" and "Back".

Figure 19. Illustration of Asphalt-Stabilized Option for Estimating Strength Properties.

part of the asphalt-stabilized base will most likely be in tension. This means that very little of the interparticle friction is mobilized. For $\phi = 0^\circ$, the cohesion is simply $\frac{1}{2} \times \text{UCS}$.

If the material is lime-stabilized and the UCS is known, click on *Lime-stabilized*. The dialog box shown in Figure 20 is displayed where you need to specify the layer number and the UCS for the lime-treated material. For these materials, the friction angle typically varies between 25 to 35 degrees (Little, 1995). A default value of 30° , is used but you may specify another angle by sliding the pointer in the dialog box to the value you wish to use, or by typing in the friction angle in the cell provided. Note that the friction angle for lime-stabilized materials is limited to be within the range of 25° to 35° in the method used to estimate strength properties for this material. Click on *Accept* to confirm your entries. The cohesion of soil-lime mixtures is estimated as 30 percent of the UCS (Little, 1995).

If the material is cement-treated and the UCS is known, you may characterize the layer as following either the Griffith or modified Griffith criterion (Raad, Monismith, and Mitchell, 1977). The application of these criteria to estimate the strength properties of cement-treated materials is explained in the appendix (in the section on stabilized materials on pages 45 to 48). Click on *Cement-treated*, and specify the criterion to use in the dialog box shown in Figure 21. Enter the layer number and UCS of the cement-treated material, then click on *Accept*. Note that the strength properties depend on the confining pressure for

Form2

UCS Option—Stabilized Materials

Asphalt Stabilized
 Lime-stabilized
 Cement-treated

Layer

UCS

$\phi = 30$

Accept

Back

Figure 20. Illustration of Lime-Stabilized Option for Estimating Strength Properties.

Form2

UCS Option—Stabilized Materials

Asphalt Stabilized
 Lime-stabilized
 Cement-treated

Layer

UCS

Modified Griffith Criterion
 Griffith Criterion

Accept

Back

Figure 21. Illustration of Cement-Treated Option for Estimating Strength Properties.

a material that behaves according to the Griffith criterion. For this reason, the cohesion and friction angle will vary within a layer so that these properties are predicted at each point where the Mohr-Coulomb yield function is evaluated. Note that the main menu will display -9.000 in the fields for cohesion and friction angle. This only identifies the material as following the Griffith criterion. The strength properties are actually predicted during run time of the analysis module of MTRX (when the triaxial design check is performed). If you want to see the predicted values of cohesion and friction angle, you need to save the results from the analysis as discussed previously. You may then open this output file in a word processor or editor (such as Notepad©) to view the strength properties as well as the predicted values of the Mohr-Coulomb yield function at the different evaluation positions.

If the material is unstabilized, click ***Unstabilized*** in the menu shown in [Figure 16](#). Then, click on ***Unconfined Compressive Strength (UCS)*** to view the dialog box ([Figure 22](#)) for estimating the strength properties of unstabilized materials. To estimate the cohesion and friction angle for these materials, you may either specify the unconfined compressive strength or the strength at another confining pressure. The latter option is provided for evaluating weak materials that may prove difficult to test at zero confining pressure.

In the dialog box, specify the layer number of the material to be characterized, its TTC and the UCS (if known). The TTC should be between 0.5 and 6.5. This material classification is used to estimate the compressive strength at 5 psi (S_5) from the following relationship developed by [Scrivner and Moore \(1967\)](#):

$$S_5 = 9.3 + 0.4539 \times (8 - \text{TTC})^3 \quad (6)$$

The predicted compressive strength at 5 psi is displayed in the dialog box when you enter the TTC of the material. This is illustrated in [Figure 22](#). Given S_5 and the compressive strength at another confining pressure, the strength properties of unstabilized materials are estimated in MTRX. If you know the UCS, click ***Only UCS*** in the dialog box and enter the UCS in the space provided. You also may specify the compressive strength at another confining pressure by clicking ***Strength at another confining pressure*** in the dialog box and entering the required data in the fields for σ_1 and σ_3 shown in [Figure 23](#). Note that the

Form2

UCS Option—Unstabilized Materials

Only UCS
 Layer

Strength at another confining pressure
 TTC(0.5<=TTC<=6.5)

Strength at 5 psi

Figure 22. Estimating Strength Properties of Unstabilized Materials from UCS.

Form2

UCS Option—Unstabilized Materials

Only UCS
 Layer
 σ_1

Strength at another confining pressure
 TTC(0.5<=TTC<=6.5)
 σ_3

Strength at 5 psi

Figure 23. Specifying the Compressive Strength at Another Confining Pressure.

compressive strength σ_1 must be for a confining pressure σ_3 other than 5 psi. This option is provided for the case where the material is too weak to test at zero confining pressure to get the UCS.

When you have entered the required information, click on **Accept** in the dialog box to confirm your entries and to estimate the cohesion and friction angle for the unstabilized material. You may then characterize the strength properties of another layer or return to the main menu by clicking on **Back** in the dialog box. The strength properties determined for the layer you characterized are displayed in the main menu.

Estimating Strength Properties Based on Texas Triaxial Class

If triaxial test data and the UCS are not available, MTRX provides an option to estimate the strength properties from the known Texas triaxial class of the material. To access this function, click on **Use Texas Triaxial Class (TTC)** in the screen shown in [Figure 16](#). This brings up the chart in [Figure 24](#) that shows the linearized forms of the TTC failure envelopes from the provisional Test Method Tex-143-E. TxDOT developed this test method in-house but has not formally adopted it at the time of this report. The linearized boundaries between classes were determined by fitting a line to each of the class boundaries in the standard Test Method Tex-117-E classification chart.

In the approximate method described herein, the linearized class boundaries in [Figure 24](#) are used to interpolate the failure envelope corresponding to the prescribed TTC. This interpolation is done such that the TTC is maintained at each point on the failure envelope. [Figure 24](#) illustrates this approach where the dashed line corresponds to the interpolated failure envelope for a TTC of 4.8.

To interpolate the failure envelope after specifying the TTC for the layer to analyze, click on **C & Angle** at the bottom of the chart to estimate the cohesion and friction angle for the material. Click on **Back** to return to the main menu where the strength properties are displayed.

NONLINEAR ANALYSIS OPTION

As mentioned earlier, MTRX provides the option of modeling the nonlinear behavior observed in most pavement materials. This capability becomes particularly important for thin pavements, which comprise a big portion of the highway network in Texas. For these

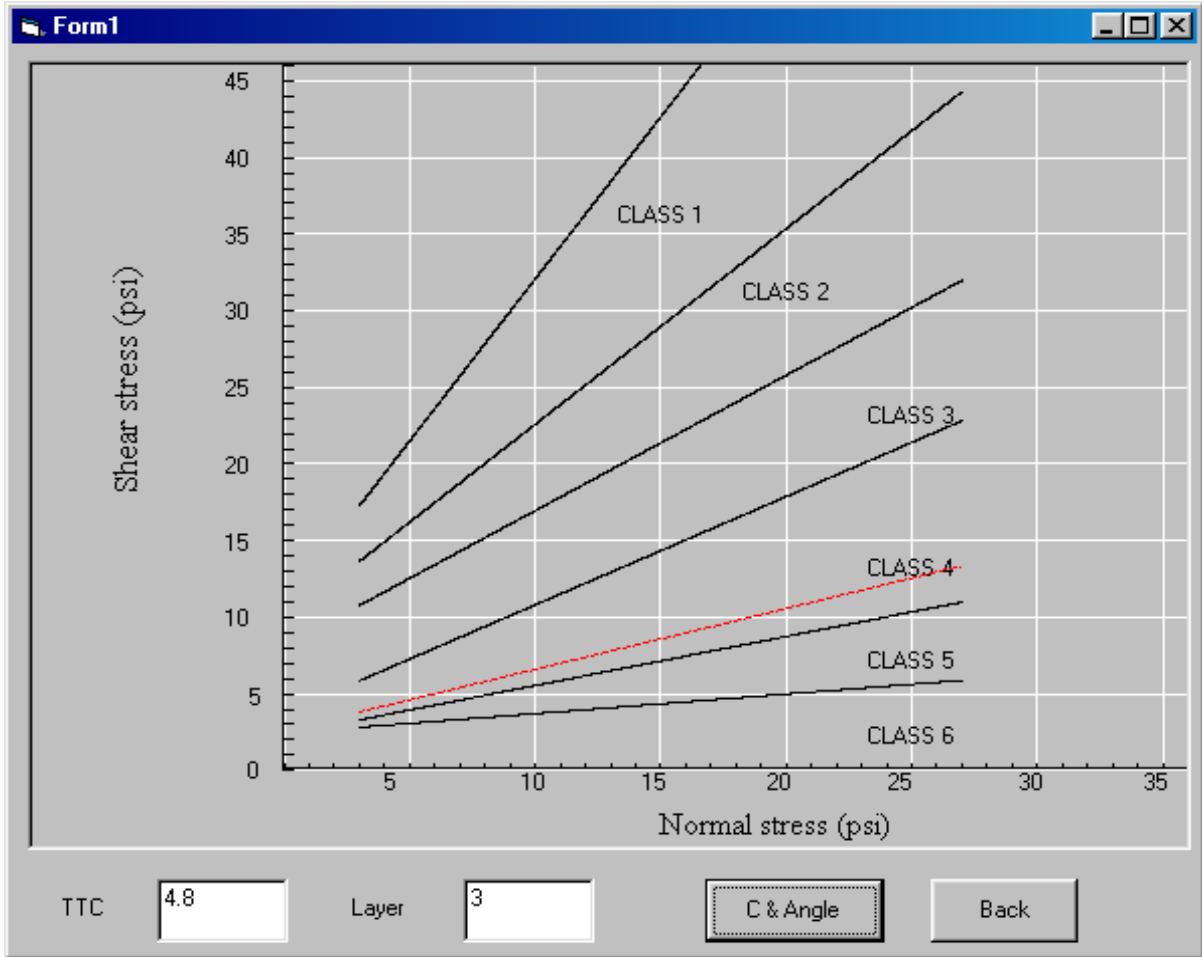


Figure 24. Estimating Strength Properties Using TTC and Tex-143-E Classification Chart.

pavements, a nonlinear analysis will provide a more realistic prediction of the stresses induced under loading (Jooste and Fernando, 1995). This analysis in MTRX uses the following equation by Uzan (1985) to model stress-dependency:

$$E = K_1 pa \left(\frac{I_1}{pa} \right)^{K_2} \left(\frac{\tau_{oct}}{pa} \right)^{K_3} \quad (7)$$

where,

- E = layer modulus,
- I_1 = first stress invariant determined from Eq. (3),
- τ_{oct} = octahedral shear stress,

pa = atmospheric pressure (14.5 psi), and
 K_1, K_2, K_3 = material constants determined from resilient modulus testing.

The octahedral shear stress may be determined from the second deviatoric stress invariant J_2 computed from Eq. (4). The relationship between τ_{oct} and J_2 is given by:

$$\tau_{oct} = \sqrt{\frac{2}{3} J_2} \quad (8)$$

The material constants of Eq. (7) may be characterized following AASHTO T-292 for unstabilized materials and ASTM D 3497 for asphalt-stabilized materials. K_2 is typically positive, indicating increased stiffness at higher confinement, while K_3 is typically negative, indicating a stiffness reduction with increased deviatoric stress. To use the nonlinear analysis option in MTRX, these constants must be characterized. No approximate methods have been incorporated in this version of the analysis program, although [Glover and Fernando \(1995\)](#) present relationships for estimating these resilient properties based on Atterberg limits, gradation, and soil suction measurements made on unstabilized materials.

If you want to use the nonlinear option for a particular project and you have the K_1 , K_2 , and K_3 coefficients for the stress-dependent pavement material(s), click ***Nonlinear*** in the main menu given in [Figure 4](#). Cells for entering the coefficients are then displayed in the menu as illustrated in [Figure 25](#). By default, the K_2 and K_3 values are initially set to zero corresponding to linear behavior, i.e., the modulus is independent of stress as inferred from Eq. (7). In this case, K_1 is simply calculated by dividing the specified modulus of the material by the atmospheric pressure of 14.5 psi. The resulting value is displayed in the main menu as shown in [Figure 25](#).

Enter the coefficients for the nonlinear pavement layer(s) in the main menu. If you want to model a layer as linear, simply leave the initial values as they are, i.e., $K_2 = K_3 = 0$, and K_1 equal to the layer modulus divided by 14.5 psi. You then may continue entering other input data as described in this manual or run an analysis as appropriate.

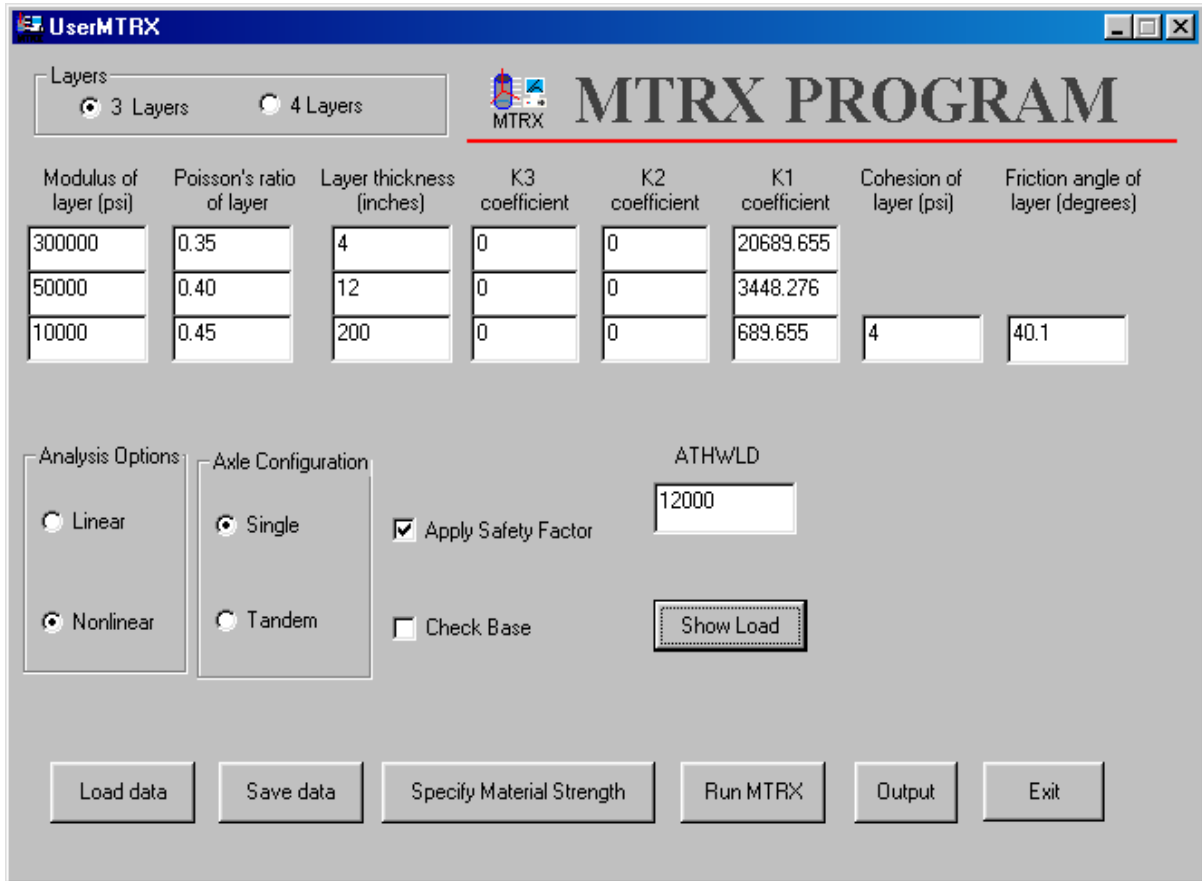


Figure 25. Specifying K_1 , K_2 , and K_3 Coefficients for Nonlinear Analysis in MTRX.

THE LEAST YOU NEED TO KNOW

To summarize, conducting a triaxial design check using MTRX will require that you at least know the following:

1. modulus, Poisson's ratio, and thickness of each pavement layer;
2. average of the ten heaviest wheel loads; and
3. Texas triaxial class of the subgrade.

The above data represent the minimum that are required to run MTRX. You may obtain these data from the flexible pavement design. Note that running the program and getting good results are two different things. To do an adequate analysis, you should know the properties of your materials and model the pavement realistically. Good engineering practice will require that you make the effort to search published information, review past experience, and/or run tests to characterize the materials for a given problem.

CHAPTER III

SUMMARY AND RECOMMENDATIONS

The preceding chapter explained the operation of the MTRX program to evaluate the structural adequacy of pavement designs based on the Mohr-Coulomb yield criterion. In the opinion of the researchers, the development of this program is a significant step toward improving the existing Texas modified triaxial design check. Among the capabilities that the program provides are:

1. input of design layer moduli and thicknesses from FPS to perform the design check;
2. characterization of pavement layers as linear materials with constant moduli or as nonlinear materials with stress-dependent moduli that obey the constitutive relationship given by Eq. (7); and
3. modeling of steering, single, and tandem axle configurations.

Since MTRX permits the user to directly input the material properties of each layer, TxDOT engineers will have the capability to model their particular environmental conditions and local materials. Thus, districts in west Texas will have the option of conducting an analysis using strength properties that correspond to in-situ moisture conditions in lieu of properties obtained under capillary saturation. Similarly, stabilized materials are characterized using modulus and strength properties instead of cohesiometer values that give only an indication of the strength of the material and are rarely characterized by the districts. Finally, MTRX permits pavement engineers to directly model the effects of different axle configurations on pavement response in lieu of applying a safety factor of 1.3 to the ATHWLD when there are more than 50 percent tandem axles in the traffic stream.

In the evaluation of structural adequacy, the Mohr-Coulomb yield criterion is checked at a number of positions within the pavement corresponding to the top, middle, and bottom of the base layer, and the top of the subgrade. At each of these depths, the stresses under load are predicted at different lateral offsets corresponding to the outside tire edge, middle of the tire, inside tire edge, and midway between dual tires as illustrated in [Figure 26](#). Additionally,

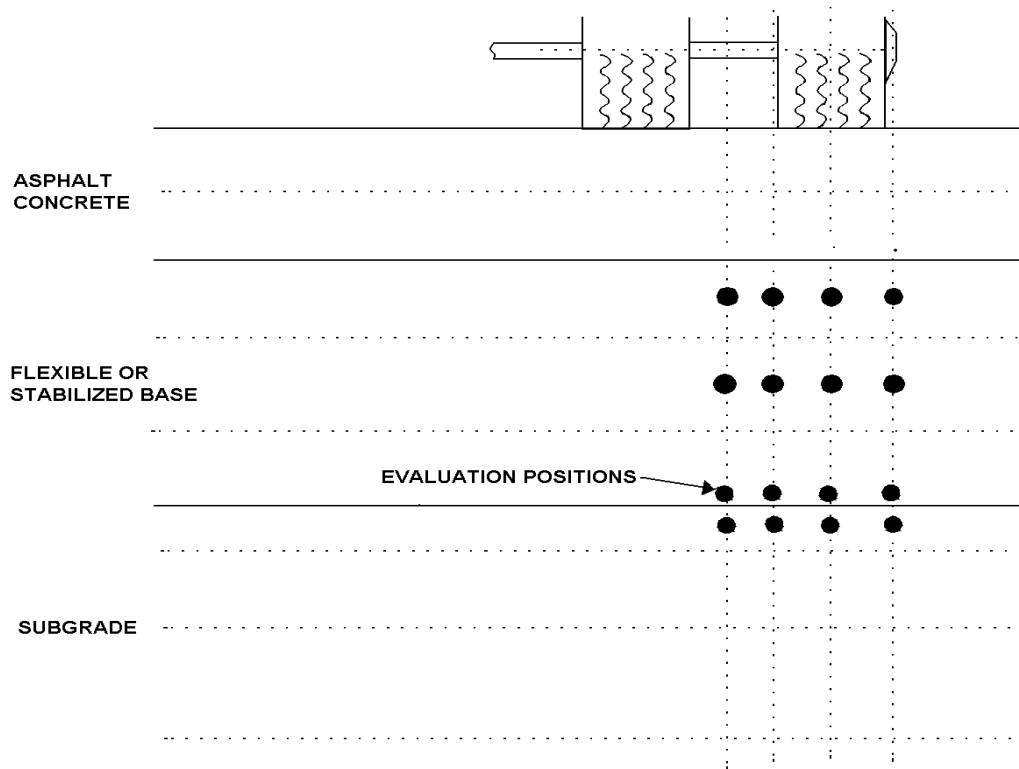


Figure 26. Locations where Stresses are Predicted for Evaluating Structural Adequacy.

for tandem axles, the stresses at the same positions are evaluated midway between the axles. At each evaluation position, the stresses are used with the Mohr-Coulomb strength properties to predict if overstressing will occur for the given pavement and design load.

While the development of MTRX represents a significant step toward updating the existing methodology to be more consistent with the mechanistic-empirical design philosophy that underpins FPS, much more work needs to be done to realize the potential benefits that implementation of this program may bring. Toward this end, the authors offer the following recommendations for further research:

1. The Mohr-Coulomb failure envelopes in the existing flexible base design chart used in Tex-117-E show a nonlinear relationship between failure stress and confining pressure. This nonlinear relationship has been observed in laboratory tests conducted by [Lu, Shih, and Scriver \(1973\)](#) for stabilized and unstabilized base materials. The form of this relationship is expressed in Eq. (18) of the

[appendix](#), which gives the model used in MTRX to characterize the Griffith criterion for cement-treated materials. The authors recommend an evaluation to verify the applicability of this model to other pavement materials. This evaluation should include a review of triaxial test data collected in previous TxDOT projects, as well as an extensive laboratory program to characterize strength properties for stabilized and unstabilized materials used by the department.

2. Before laboratory tests are carried out, researchers should initially develop a test plan that will identify the types of materials to be tested, the factors that will be included in the experiments, and the measurements to be made. The effect of moisture content on the Mohr-Coulomb strength properties should be investigated to develop guidelines for characterizing these properties that consider the different environmental regions of the state. The authors also recommend that the laboratory program include characterizations of the stress-dependent behavior of the materials to be tested. The results from these tests will be useful in developing procedures to establish the K_1 , K_2 , and K_3 coefficients of Eq. (7) for implementing the nonlinear analysis option in MTRX. In view of the upcoming release of the 2002 American Association of State Highway and Transportation Officials (AASHTO) pavement design guide, the resilient modulus tests proposed herein may also be conducted as part of a larger effort of evaluating and implementing the AASHTO 2002 pavement design procedure within TxDOT.
3. The options available in MTRX for estimating strength properties should be updated accordingly based on analysis of the triaxial data collected from the laboratory test program. In addition, the program should be updated to include options for estimating the stress-dependent material parameters for the nonlinear analysis.
4. A pilot implementation program should be conducted in selected districts to introduce MTRX to TxDOT pavement design engineers who are expected to be the primary users of this analysis procedure. The authors recommend that this implementation be conducted on actual projects where demonstrations are

provided that show how test data needed for the design check are established. In addition, training on the application of the MTRX program should be provided.

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APPENDIX

PROCEDURES FOR SPECIFYING STRENGTH PROPERTIES

To perform a design check using the MTRX program, the user must specify the cohesion and friction angle that define the Mohr-Coulomb failure envelope and the Texas triaxial class of a given material. The authors recommend that these properties be determined from triaxial tests on the materials selected for designing and constructing a given pavement. For this determination, you may use MTRX to get the strength properties from triaxial test data as presented in [Chapter II](#) of this report. However, the authors recognize that data from laboratory tests will not always be available for determining the strength properties that are input to the analysis program. To facilitate implementation, the authors included a number of options in MTRX that the engineer may use to specify these properties. These options, which were developed using results from previous investigations, are described in the following.

RELATIONSHIP BETWEEN TEXAS TRIAXIAL CLASS AND COMPRESSIVE STRENGTH

Using data from triaxial tests conducted by the Bryan District on 106 pavement materials, [Scrivner and Moore \(1967\)](#) developed the following relationship between the Texas triaxial class and the compressive strength at a confining pressure of 5 psi:

$$S_5 = 9.3 + 0.4539 (8 - \text{TTC})^3 \quad (9)$$

where,

S_5 = predicted compressive strength in psi, and

TTC = Texas triaxial class restricted to the interval, $0.5 \leq \text{TTC} \leq 6.5$.

[Figure 27](#) shows how the above relationship fits the triaxial test data. [Scrivner and Moore \(1967\)](#) did not report goodness-of-fit statistics for Eq. (9). However, it is observed from [Figure 27](#) that the equation fits the data points quite well. Moreover, Scrivner and Moore conducted an independent verification of Eq. (9) using additional data from triaxial tests

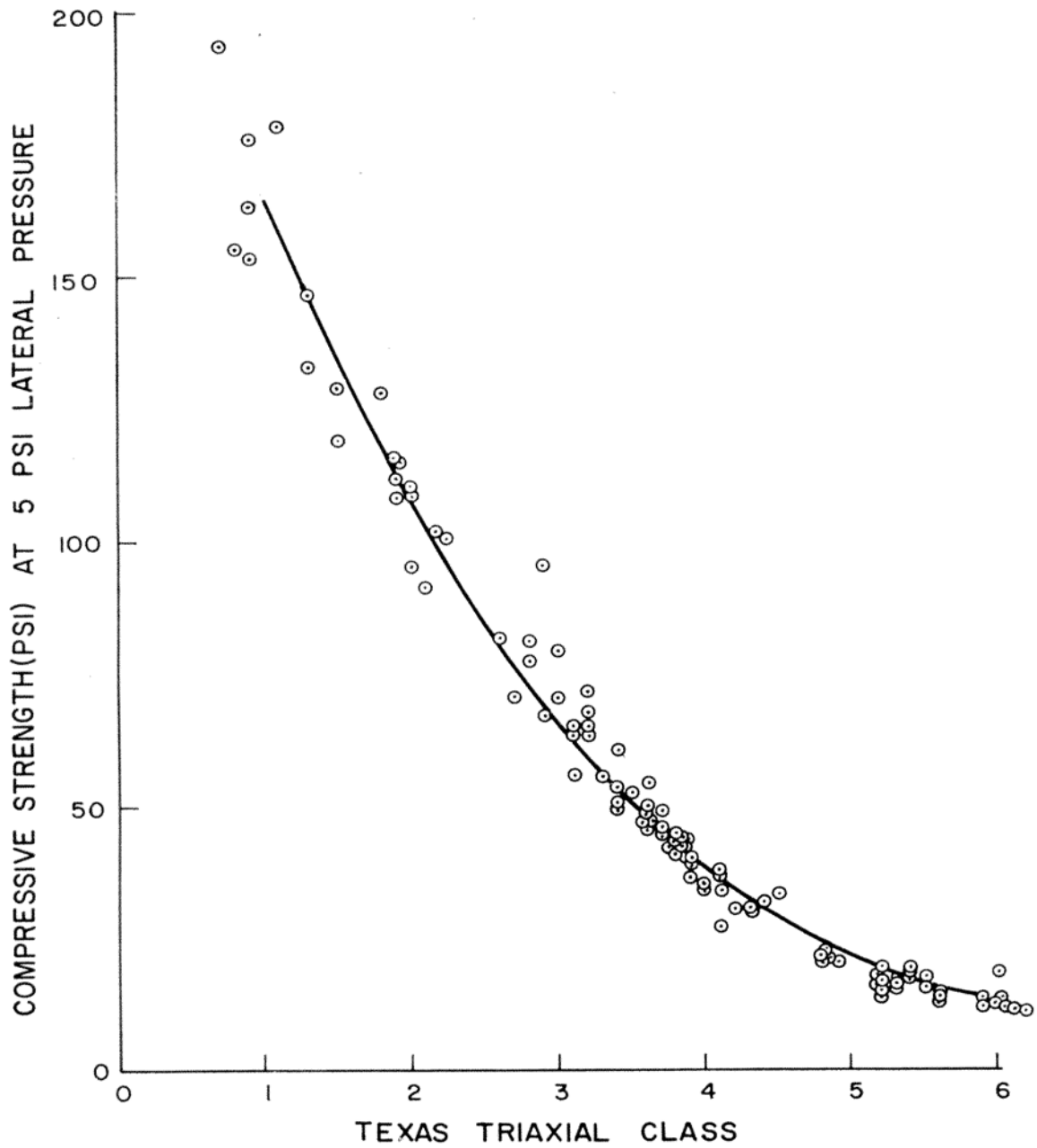


Figure 27. Relationship between TTC and Compressive Strength at 5 psi Confining Pressure from Tests Conducted by Bryan District (Scrivner and Moore, 1967).

done on 113 different materials obtained from 13 districts. [Figure 28](#) shows how the equation fits the additional data obtained. Note that the data points shown in the figure were not used in developing Eq. (9). Considering the reasonable fit, [Figure 28](#) indicates that Eq. (9) is fairly robust.

While an estimate of TTC may be obtained from Eq. (9) given S_5 , using the equation in an inverse manner is not recommended. Equation (9) is derived by curve fitting laboratory data so that the coefficients of the equation depend on the choice of independent and dependent variables. Also, note that the equation is valid for TTCs within the range of 0.5 to 6.5. Compressive strengths determined for TTCs outside this range represent extrapolated values.

It is also noted that [Figures 27](#) and [28](#) include data points where the TTCs are below 2.0. These values were obtained using the special classification chart shown ([Figure 29](#)) that includes a line for Class 1 materials derived by [Scrivner and Moore \(1966\)](#) from extrapolation of the lines for Class 2, 3, 4, and 5 materials. Researchers used the Class 1 curve shown in [Figure 29](#) to add a Class 1 line to the linearized classification chart used in MTRX to estimate the Mohr-Coulomb strength properties given the TTC.

Equation 9 is applicable for unstabilized materials. Knowing the compressive strength, the Mohr's circle for a confining pressure of 5 psi may be constructed. However, to determine the cohesion and friction angle, the Mohr's circle at an additional confining pressure is needed. If the unconfined compressive strength of the material is known, these properties may be estimated from the following relations, which the researchers derived using Mohr-Coulomb failure theory:

$$\phi = \sin^{-1} \left(\frac{UCS - S_5 + 5}{UCS - S_5 - 5} \right) \quad (10)$$

and

$$c = \frac{UCS \sin \phi (1 - \sin \phi)}{\sin 2\phi} \quad (11)$$

where,

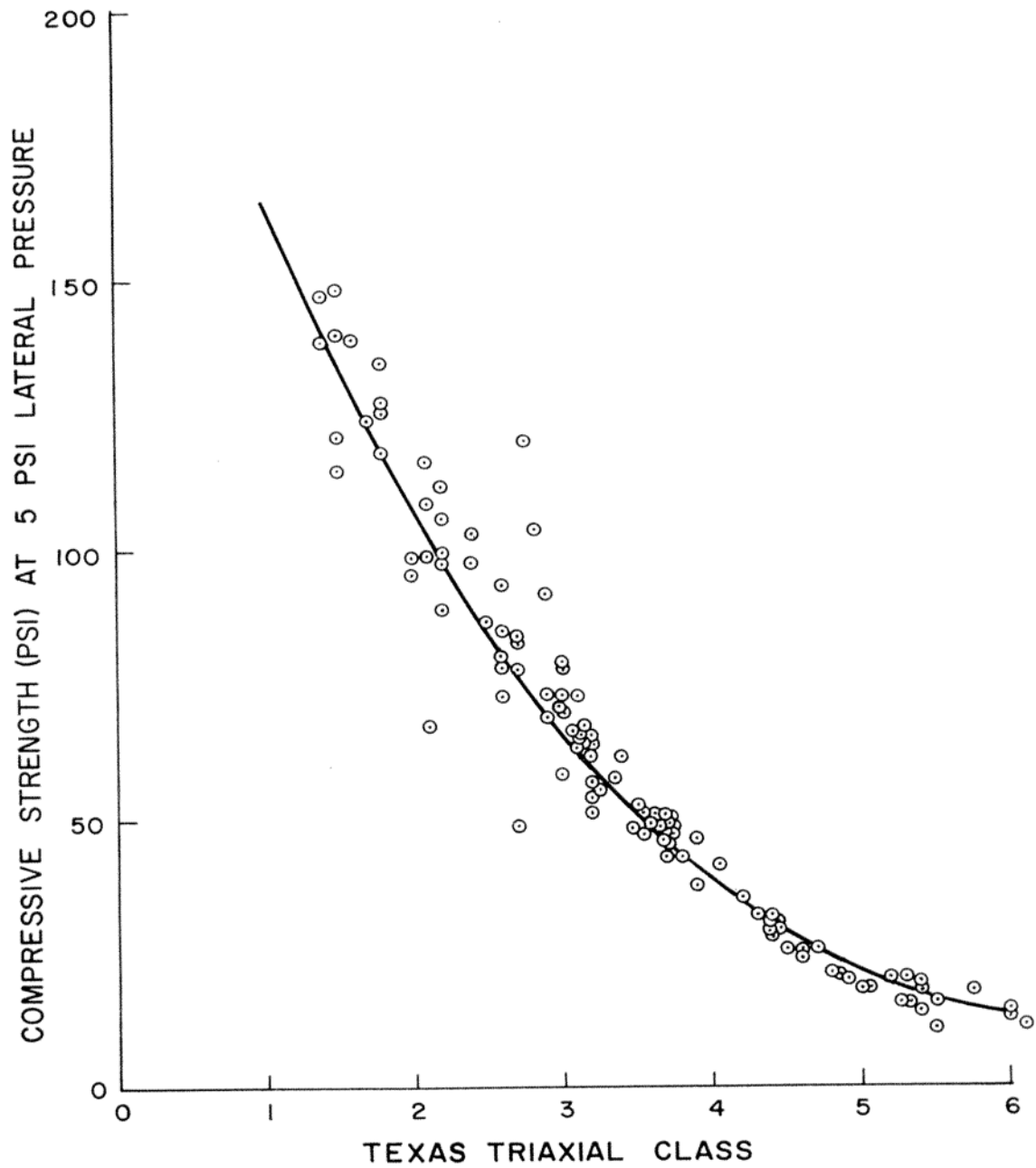


Figure 28. Verification of Relationship for Predicting Compressive Strength at 5 psi Confining Pressure Using Data from Other Districts (Scrivner and Moore, 1967).

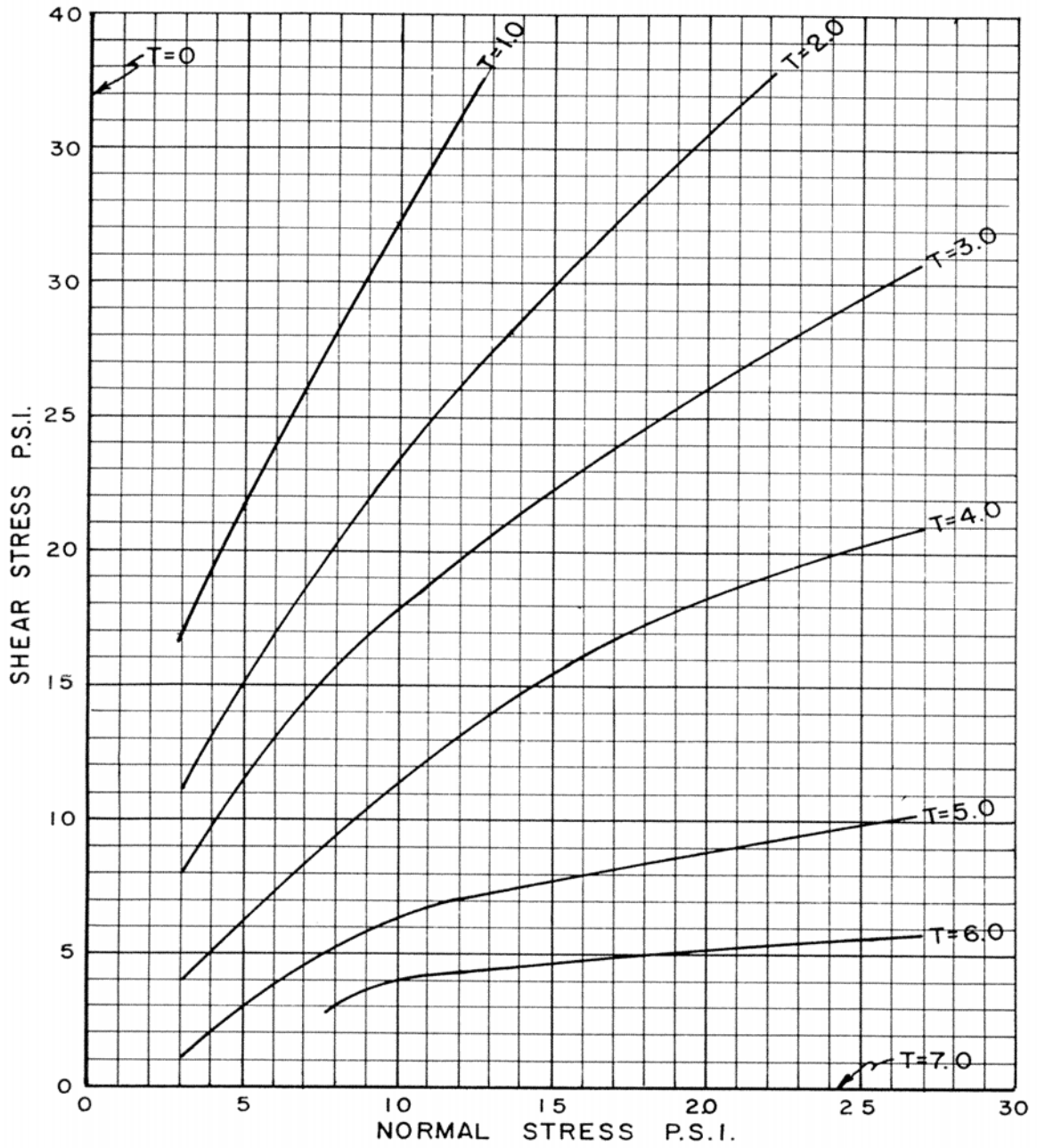


Figure 29. Texas Triaxial Classification Chart with Class 1 Line (Scrivner and Moore, 1967).

- ϕ = friction angle,
 c = cohesion, psi,
 UCS = unconfined compressive strength (psi), $0 \leq UCS \leq (S_5 - 5)$, and
 S_5 = predicted compressive strength at 5 psi confining pressure from Eq. (9).

The unconfined compressive strength may be obtained from previous data or from actual laboratory tests. For weak materials (Class 5 and lower) it may be difficult to run a test at zero confining pressure to determine the UCS. For these unstabilized materials, it may be necessary to apply a confining pressure to determine the Mohr's circle of stress. In this instance, if the applied confining pressure is denoted as σ_3 , and the compressive strength determined from the test is denoted as σ_1 , the strength properties are determined from the following relations:

$$\phi = \text{Sin}^{-1} \left[\frac{(\sigma_1 - \sigma_3) - (S_5 - 5)}{(\sigma_1 + \sigma_3) - (S_5 + 5)} \right] \quad (12)$$

and

$$c = \frac{\sigma_1 \sin \phi (1 - \sin \phi) - \sigma_3 \sin \phi (1 + \sin \phi)}{\sin 2\phi} \quad (13)$$

where the terms are as defined previously. Note that Eqs. (12) and (13) reduce to Eqs. (10) and (11) respectively at zero confining pressure ($\sigma_3 = 0$) for which $\sigma_1 = UCS$. Equations (9), (10), and (11) may be used to estimate the Mohr-Coulomb strength properties of unstabilized materials given the TTC and UCS, while Eqs. (9), (12), and (13) are used if the TTC and the failure stress from a triaxial test conducted at another confining pressure ($\sigma_3 \neq 0$ and $\sigma_3 \neq 5$ psi) are available.

Note that the cohesion and friction angle of unstabilized soils are influenced by moisture content. Since the TTC in Eq. (9) is determined from tests on soil specimens that have undergone capillary saturation, the compressive strength at the other confining pressure must also be determined under the same moisture condition for the strengths to be comparable. Thus, the cohesion and friction angle determined using Eqs. (9), (10), and (11), or Eqs. (9), (12), and (13) are based on capillary saturated specimens consistent with Test Method Tex-117-E.

STABILIZED MATERIALS

The unconfined compressive strength may be used in evaluating the load carrying capacity of stabilized materials. In the absence of laboratory triaxial test data, one approach that may be used for asphalt-stabilized layers is to assume the friction angle to be zero ($\phi = 0$ condition) and compute the cohesion as:

$$c = \frac{1}{2} UCS \quad (14)$$

For stabilized base materials, the critical region will likely be at the bottom of the base underneath the load where tensile stresses are likely to be induced. Under this condition, the strength attributed to interparticle friction will likely be minimal since the material is being pulled apart. Thus, the load carrying capacity will depend, to a large extent, on the cohesion of the material. From this perspective, there is a rationale for using the above approach to evaluate the load carrying capacity of asphalt-stabilized materials in the absence of triaxial test data. The laboratory test program recommended in [Chapter III](#) should provide data that can be used to verify this approach.

For soil-lime mixtures, the major effect of lime stabilization is to increase the cohesion of the material ([Little, 1995](#)). The cohesion is observed to increase with mixture compressive strength and may be roughly approximated at 30 percent of UCS. Some minor increase in the friction angle is observed with lime stabilization. For these materials, the friction angle typically varies from 25° to 35°.

For cement-stabilized materials, the Griffith criterion has been proposed to characterize the relationship between failure stress and confining pressure. [Figure 30](#) shows triaxial test data for a number of cement-treated materials. The data were obtained from triaxial tests on soil cements used in pavement base layers, embankments, and dams and from tests conducted on concrete materials under biaxial loading conditions. It is observed that the data points appear to follow a fairly well-defined trend when the failure stress and confining pressure are normalized by the unconfined compressive strength denoted by the symbol, σ_{unc} , in [Figure 30](#). Also shown are two criteria that have been proposed to model the relationship between failure stress and confining pressure for cement-treated materials. These criteria are the Griffith and the modified Griffith criteria. Most of the data points in [Figure 30](#) are observed to follow the modified Griffith criterion, which is defined by the following linear equation:

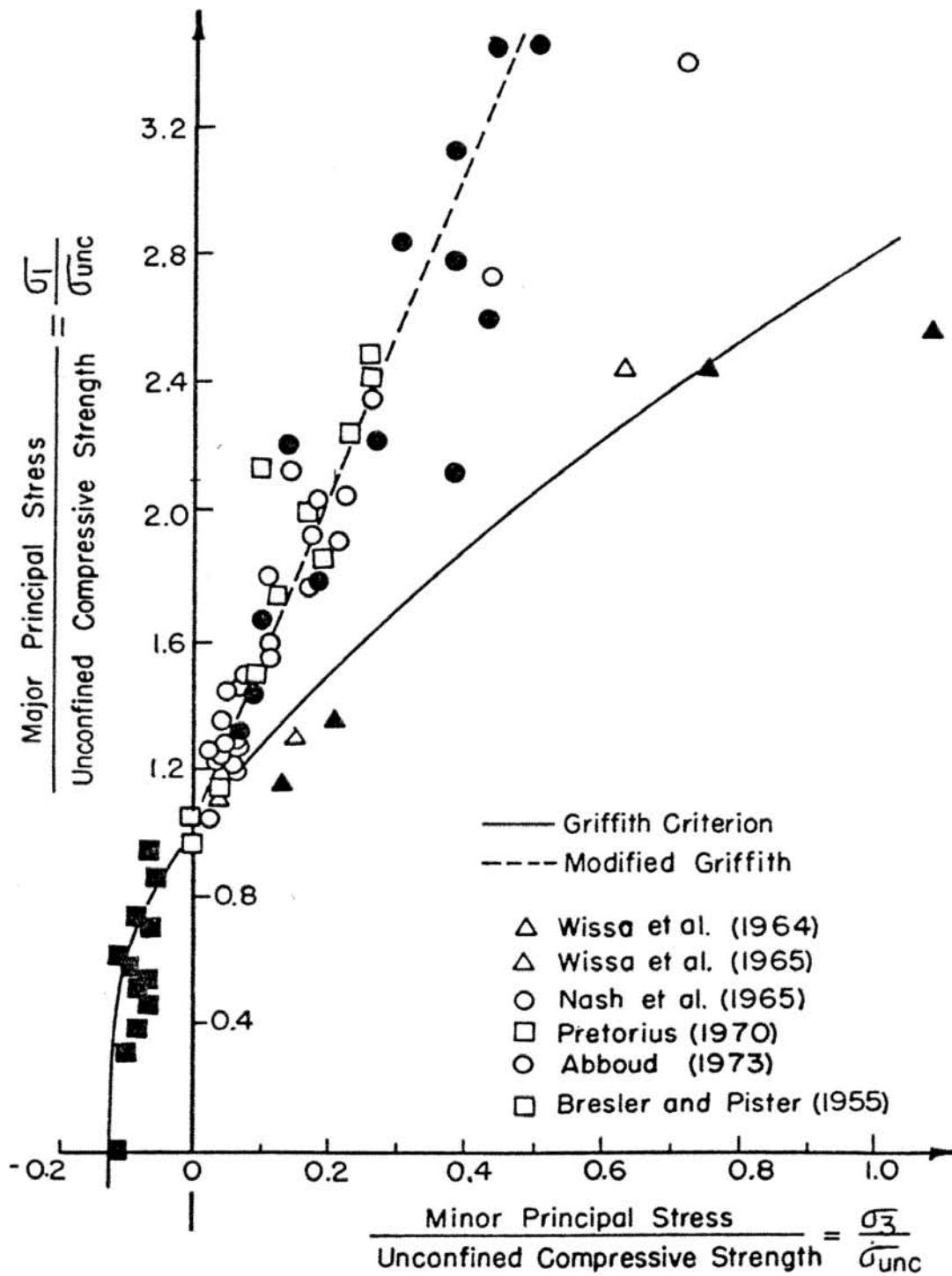


Figure 30. Normalized Failure Envelopes for Cement-Treated Soils (Raad, Monismith, and Mitchell, 1977).

$$\sigma_1' = \beta_0 + \beta_1 \sigma_3' \quad (15)$$

where,

$$\begin{aligned} \sigma_1' &= \sigma_1 / \sigma_{\text{unc}}, \\ \sigma_3' &= \sigma_3 / \sigma_{\text{unc}}, \\ \sigma_{\text{unc}} &= \text{unconfined compressive strength (UCS)}, \\ \sigma_3 &= \text{applied confining pressure in the triaxial test}, \\ \sigma_1 &= \text{measured failure stress corresponding to } \sigma_3, \text{ and} \\ \beta_0, \beta_1 &= \text{model coefficients.} \end{aligned}$$

Using Eq. (15), researchers derived the following relationships for estimating ϕ and c for cement-stabilized materials following Mohr-Coulomb failure theory:

$$\phi = \text{Sin}^{-1} \left(\frac{\beta_1 - 1}{\beta_1 + 1} \right) \quad (16)$$

and

$$c = \frac{\beta_0 \text{UCS}}{2\sqrt{\beta_1}} \quad (17)$$

From [Figure 30](#), the coefficients of the modified Griffith criterion are determined to be $\beta_0 \approx 0.9$ and $\beta_1 \approx 6$. Thus, based on the modified Griffith criterion, the failure envelopes for cement-treated materials are a family of lines of constant slope, $\phi \approx 45.6^\circ$, with y-intercepts or cohesion values that are approximated by $c \approx 0.18 \text{ UCS}$. Physically, this means that the Mohr's circles of stress expand in proportion to the unconfined compressive strength of the material consistent with the linear relationship assumed in Eq. (15).

The Griffith criterion in [Figure 30](#) defines a lower boundary of the data plotted in the chart. For a given confining pressure, the Griffith criterion will predict a lower failure stress than the modified criterion given in Eq. (15) and is, thus, more conservative. The following model may be used to define the nonlinear relationship between failure stress and confining pressure that is assumed in the Griffith criterion:

$$\sigma_1' = \alpha_0 \left(1 + \frac{\sigma_3'}{\alpha_1} \right)^{\alpha_2} \quad (18)$$

where, α_0 , α_1 , and α_2 are model coefficients and the other terms are as defined previously. The coefficients α_0 , α_1 , and α_2 are 1.0, 0.125, and 0.462, respectively. Researchers determined these coefficients by digitizing the Griffith curve in [Figure 30](#) and fitting Eq. (18) to the digitized points by nonlinear regression. The root-mean-square error of the fitted curve from the regression is 0.009 with 123 digitized points.

Equation (18) reduces to $\sigma_1 = \sigma_{unc} = UCS$ when the confining pressure, $\sigma_3 = 0$. Also, it may be discerned from Eq. (18) and [Figure 30](#) that $\alpha_1 \times UCS$ is an estimate of the tensile strength of the material. If Eq. (18) is used to model Griffith's criterion, the following equations for estimating friction angle and cohesion are determined:

$$\phi = \text{Sin}^{-1}\left(\frac{A-1}{A+1}\right) \quad (19)$$

where,

$$A = \frac{\alpha_0 \alpha_2}{\alpha_1} \left(1 + \frac{\sigma_3'}{\alpha_1}\right)^{\alpha_2 - 1} \quad (20)$$

and,

$$c = \frac{UCS}{2} \left[\left(\frac{\alpha_0 \alpha_1}{\alpha_2}\right)^{1/2} \left(1 + \frac{\sigma_3'}{\alpha_1}\right)^{\frac{1+\alpha_2}{2}} - \sigma_3' \left(\frac{\alpha_0 \alpha_2}{\alpha_1}\right)^{1/2} \left(1 + \frac{\sigma_3'}{\alpha_1}\right)^{\frac{\alpha_2-1}{2}} \right] \quad (21)$$

The nonlinear relationship between failure stress and confining pressure has been observed in laboratory tests conducted by [Lu, Shih, and Scrivner \(1973\)](#) for stabilized and unstabilized materials. Because of this, the resulting failure envelope is also nonlinear so that Eqs. (19) to (21) define the tangent to the failure envelope at a given confining pressure.

GRAPHICAL METHODS

If the TTC and the cohesion or friction angle of a material are known, the failure envelope may be uniquely determined using the classification chart shown in [Figure 29](#).

In certain cases, however, the only information that may be known about a material is its Texas triaxial class. The TTC is determined by overlaying the failure envelope on the chart shown in [Figure 29](#) and locating the point on the envelope farthest from the upper class line. However, given only the TTC, it is not possible to uniquely determine the failure envelope since any number of lines may be made to pass the point. To provide an approximate method to evaluate structural adequacy, assumptions must be made to interpolate a failure envelope from the classification chart, given only the Texas triaxial class. In the approximate procedure used in MTRX, the class lines in [Figure 29](#) are linearized as illustrated in [Figure 31](#). In this figure, the solid lines represent the classes included in the classification chart given in Test Method Tex-117-E. The dashed lines are the linearized class boundaries that are proposed in the new triaxial test method designated as Tex-143-E. MTRX uses these linearized class boundaries to interpolate the failure envelope corresponding to a prescribed Texas triaxial class. This interpolation is done such that the specified TTC is maintained at each point on the failure envelope as illustrated in [Figure 24](#). MTRX then uses the interpolated envelope to predict if overstressing of the material will occur for the prescribed loading and pavement structure.

TRIAXIAL TESTING OF PAVEMENT MATERIALS

While the previous sections have presented methods for estimating the strength properties of pavement materials, the authors recommend direct characterization of the failure envelope from laboratory tests. This characterization may be done following Tex-117-E or the provisional procedure designated as Tex-143-E once TxDOT formally adopts it. In this latter method, the specimen is encased in an elastic membrane and placed inside an acrylic cell that can be filled with water or air for application of the confining pressure. Typically, specimens are tested at confining pressures of 3, 7, and 10 psi. Given the failure stresses at different confining pressures, the failure envelope may be determined through a numerical procedure that finds the cohesion and friction angle values, c and ϕ , resulting in the best fit to the following equation:

$$\frac{\sigma_1}{\sigma_3} = \frac{2c \cos \phi + (1 + \sin \phi) \sigma_3}{\sigma_3 (1 - \sin \phi)} \quad (22)$$

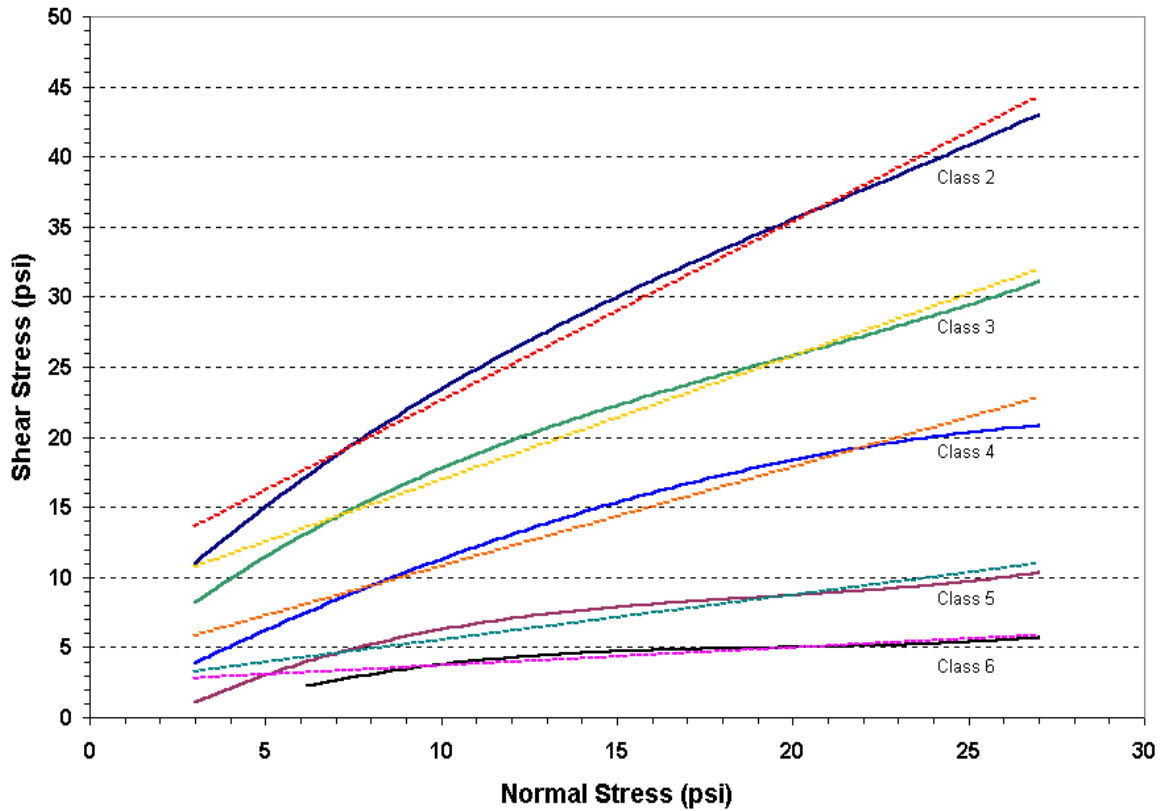


Figure 31. Linear Regression Lines Fitted to Tex-117E TTC Curves.

where the corresponding pairs of failure stresses (σ_1) and confining pressures (σ_3) are determined from the tests. At the very least, triaxial tests must be done at two confining pressures. For this case, if the failure stresses, corresponding to confining pressures of σ_3 and σ_3' , are denoted as σ_1 and σ_1' , respectively, the Mohr-Coulomb strength properties are determined directly from the following equations:

$$\phi = \text{Sin}^{-1} \left[\frac{(\sigma_1 - \sigma_3) - (\sigma_1' - \sigma_3')}{(\sigma_1 + \sigma_3) - (\sigma_1' + \sigma_3')} \right] \quad (23)$$

and

$$c = \frac{\sigma_1 \sin \phi (1 - \sin \phi) - \sigma_3 \sin \phi (1 + \sin \phi)}{\sin 2\phi} \quad (24)$$

SUMMARY

This appendix presented different options for characterizing the failure envelopes of pavement materials that MTRX requires to evaluate structural adequacy. In this new program, the stresses induced under load are predicted using a layered elastic pavement model, which permits a linear or nonlinear characterization of pavement materials. Steering, single, and tandem axle configurations may be modeled directly in the computer program.

The predicted stresses at critical locations within the base and subgrade layers are checked against the Mohr-Coulomb yield criterion to evaluate whether the given pavement will sustain a single application of the prescribed load without undergoing a rapid shear failure. This approach is consistent with the theoretical basis for the existing modified triaxial design procedure. Note that the development of permanent deformation due to repeated traffic loading is not considered in this design check nor in the current FPS-19 design program. The researchers recommend that future work incorporate this distress mode as a design criterion in FPS.

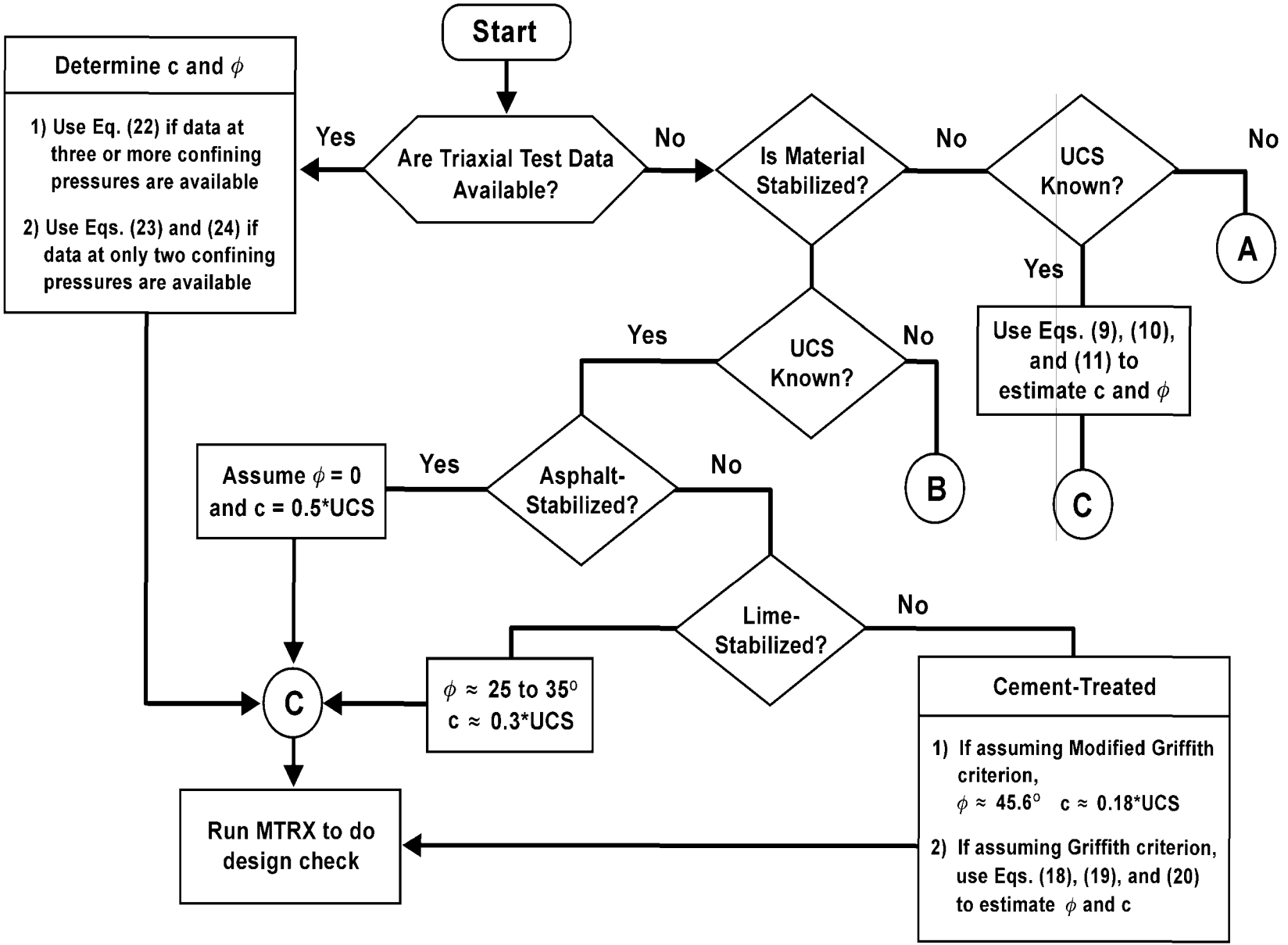
To evaluate the potential for rapid shear failure under a single load application, the failure envelopes of the base and subgrade materials are specified through input of the cohesion and friction angle values. It is emphasized that these properties are influenced by moisture content. Consequently, it is important to characterize these properties for the expected in-service conditions, which range from dry to wet as one goes from west to east Texas.

MTRX incorporates the options presented in this appendix for determining or estimating the Mohr-Coulomb strength parameters. [Table 1](#) summarizes the available options, while [Figure 32](#) shows a flowchart of the computer program. Future work should include laboratory tests to verify the options presented for estimating the strength properties, particularly for the stabilized materials used in the state for which very limited triaxial test data are available.

Table 1. Options for Specifying Mohr-Coulomb Strength Properties.

Condition	Option
A. Triaxial test data at two or more confining pressures are available:	Use Eq. (22) to find ϕ and c given the failure stresses at three or more confining pressures, or Eqs. (23) and (24) if triaxial test data are available at only two confining pressures.
B. If there are no triaxial test data at two or more confining pressures, then:	
If material is unstabilized and the UCS is known or triaxial test data at another confining pressure are available:	Use Eqs. (10) and (11) to estimate ϕ and c , respectively, given the UCS, or Eqs. (12) and (13) if triaxial test data at another confining pressure are available.
If material is asphalt stabilized:	Assume $\phi = 0$ and estimate cohesion from Eq. (14); or
If lime stabilized and UCS is known:	Assume ϕ between 25° and 35° and estimate $c \approx 0.30$ UCS
If cement-treated and UCS is known:	Assume the modified Griffith criterion and use Eqs. (16) and (17) to estimate strength properties, or assume the Griffith criterion and use Eqs. (19), (20), and (21).
C. If triaxial test data and UCS are not available, then:	
If only TTC is known	Interpolate failure envelope using linearized class boundaries from Tex-143-E

Figure 32. Flowchart of Options for Specifying Mohr-Coulomb Strength Properties in MTRX.



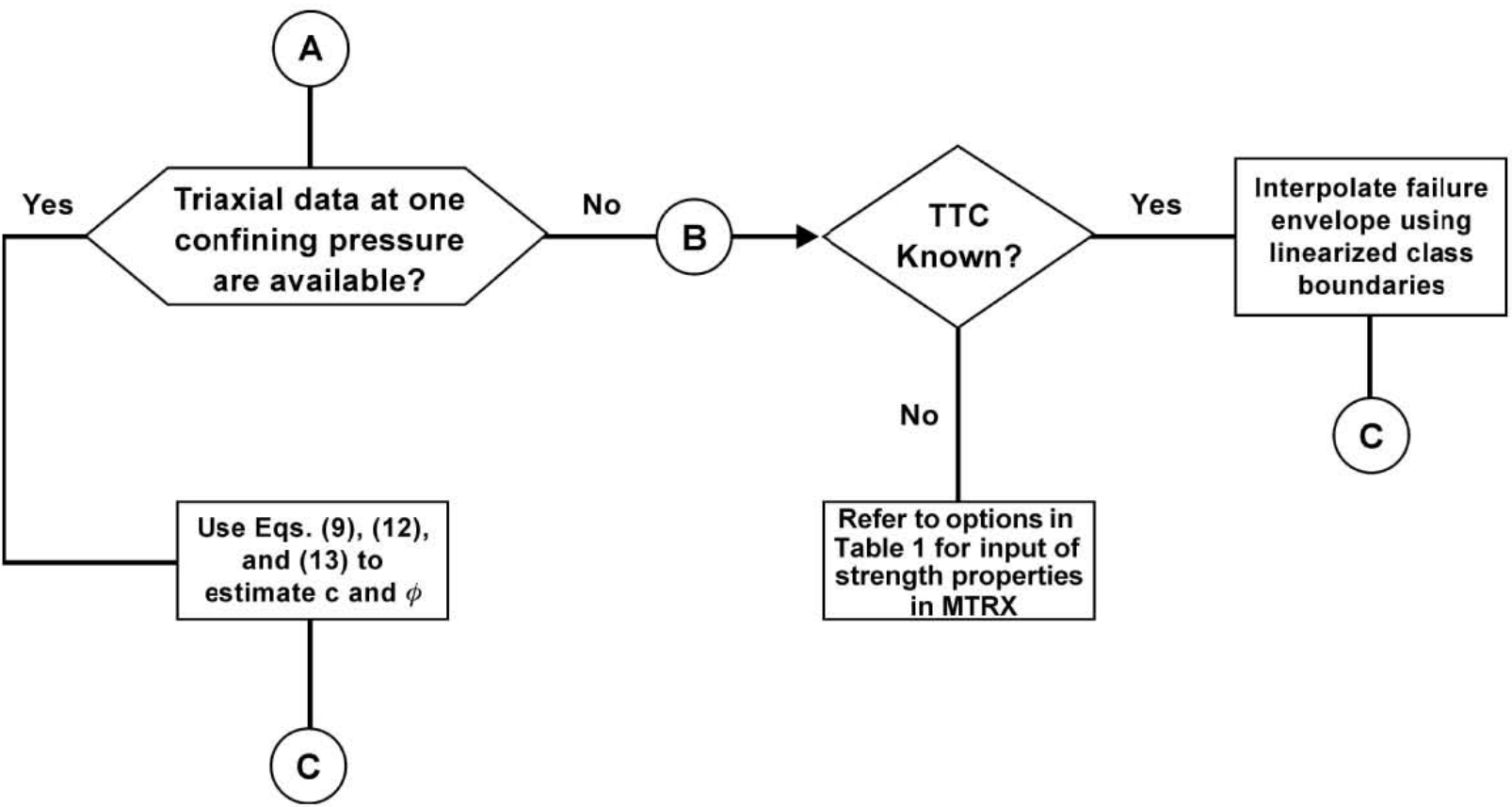


Figure 32. Flowchart of Options for Specifying Mohr-Coulomb Strength Properties in MTRX (continued).

